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Implementation of a new flux rotor based on model reference adaptive system for sensorless direct torque control modified for induction motor

Introduction. *In order to realize an efficient speed control of induction motor, speed sensors, such as encoder, resolver or tachometer may be utilized. However, some problems appear such as, need of shaft extension, which decreases the mechanical robustness of the drive, reduce the reliability, and increase in cost.* ***Purpose.*** *In order to eliminate of speed sensors without losing. Several solutions to solve this problem have been suggested. Based on the motor fundamental excitation model, high frequency signal injection methods. The necessity of external hardware for signal injection and the adverse influence of injecting signal on the motor performance do not constitute an advantage for this technique. Fundamental model-based strategies method using instantaneous values of stator voltages and currents to estimate the rotor speed has been investigate. Several other methods have been proposed, such as model reference adaptive system, sliding mode observers, Luenberger observer and Kalman filter. The* ***novelty*** *of the proposed work consists in presenting a model reference adaptive system based speed estimator for sensorless direct torque control modified for induction motor drive. The model reference adaptive system is formed with flux rotor and the estimated stator current vector.* ***Methods.*** *The reference model utilizes measured current vector. On the other hand, the adjustable model uses the estimated stator current vector. The current is estimated through the solution of machine state equations.* ***Practical value****. The merits of the proposed estimator are demonstrated experimentally through a test-rig realized via the dSPACE DS1104 card in various operating conditions. The experimental results show the efficiency of the proposed speed estimation technique. Experimental results show the effectiveness of the proposed speed estimation method at nominal speed regions and speed reversal, and good results with respect to measurement speed estimation errors obtained.* References 20, table 1, figures 9.

Key words: **induction motor, model reference adaptive system, sensorless speed, direct torque control.**

Вступ*. Щоб реалізувати ефективне керування швидкістю асинхронного двигуна, можна використовувати датчики швидкості, такі як енкодер, резольвер або тахометр. Однак виникають деякі проблеми, такі як необхідність подовження валу, що знижує механічну міцність приводу, знижує надійність та збільшує вартість.* ***Мета****. Для усунення датчиків швидкості без втрати. Було запропоновано кілька рішень на вирішення цієї проблеми. На основі моделі основного порушення двигуна використовуються методи подачі високочастотного сигналу. Необхідність зовнішнього обладнання для подачі сигналу та несприятливий вплив подачі сигналу на роботу двигуна не є перевагою цього методу. Досліджено метод стратегій на основі фундаментальних моделей з використанням миттєвих значень напруг та струмів статора для оцінки швидкості обертання ротора. Було запропоновано кілька інших методів, таких як еталонна адаптивна система моделі, спостерігачі режиму ковзання, спостерігач Люенбергера і фільтр Калмана.* ***Новизна*** *запропонованої роботи полягає у поданні модельної еталонної адаптивної системи оцінки швидкості прямого бездатчикового управління моментом, модифікованої для асинхронного електроприводу. Еталонна адаптивна система моделі формується з магнітним потоком ротора та оціненим вектором струму статора.* ***Методи.*** *Еталонна модель використовує вимірюваний вектор струму. З іншого боку, модель, що регулюється, використовує передбачуваний вектор струму статора. Струм оцінюється шляхом вирішення рівнянь стану машини.* ***Практична цінність****. Переваги запропонованого оцінювача продемонстровані експериментально на тестовій установці, реалізованій на платі dSPACE DS1104 у різних умовах експлуатації. Експериментальні результати свідчать про ефективність запропонованої методики оцінки швидкості. Експериментальні результати показують ефективність запропонованого методу оцінки швидкості в областях номінальних швидкостей та реверсивних швидкостей, а також хороші результати щодо отриманих похибок оцінки швидкості вимірювання.* Бібл. 20, табл. 1, рис. 9.

Ключові слова: **асинхронний двигун, еталонна адаптивна система, бездатчикова швидкість, пряме управління крутним моментом.**

Introduction. Speed information is mandatory for the operation of a modified direct torque control (DTC) for induction motor (IM) based on amplitude and angle control of stator flux.

The rotor speed can be measured through a sensor or may be estimated using voltage, current signals and the information of machine parameters. Use of speed sensor is associated with problems, such as, reduction of mechanical robustness of the drive, need of shaft extension, reduced reliability in hazardous environment, and increased cost. Therefore, a speed sensorless drive has a clear edge over the traditional vector controlled drive [1].

The motor speed for sensorless control can be estimated by different methods [2-5]. The simplest technique is based on the rotor flux vector coordinates obtained using the induction motor model, based on the slip calculation and angular velocity of rotor flux vector. This technique is very popular and quite simple to implement, but the obtained precision is very bad due to a great sensitiveness to motor parameter uncertainties. The other techniques are based on the extended Kalman filters or extended Luenberger observers [3, 5], which are very robust to the induction motor parameter variations or identification errors, but are very more complex and difficult in technical realization. The other solution for speed estimation is based on the model reference adaptive system (MRAS) principle, in which an error vector is created from the outputs of two models, both dependent on different motor parameters. The error is driven to zero through adjustment of a parameter that affects one of models.

The MRAS approach has the characteristic in the simplicity and easy of used models, which are simulators of chosen electromagnetic state variables of the induction machine, in comparison with extended state observers or Kalman filters or nonlinear. Thus they are easy in and simple implementation and have direct physical interpretation.

The basic structure of the MRAS is shown in Fig. 1. The error signal may be formulated with flux [6-10], back-EMF, reactive power and active power [11-16]. The flux-based MRAS (F-MRAS) is first introduced in [6].

The goal of the work is to develop a model reference adaptive system with flux rotor for speed estimation of sensorless control of induction motor drive. The reference model utilizes measured current vector. On the other hand, the adjustable model uses the estimated stator current vector. The current is estimated through the solution of machine state equations. Current, being a vector quantity, is configured in terms of flux rotor.

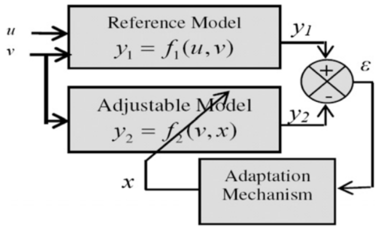

Fig. 1. Basic structure of MRAS

Proposed speed estimator. The structure of the proposed MRAS (F-MRAS) is shown in Fig. 2, which utilizes (1) in the reference model and (2) in the adjustable model. Note that both the models are in stationary reference frame. Measured current is used in the reference model, whereas estimated current is considered for the adjustable model.

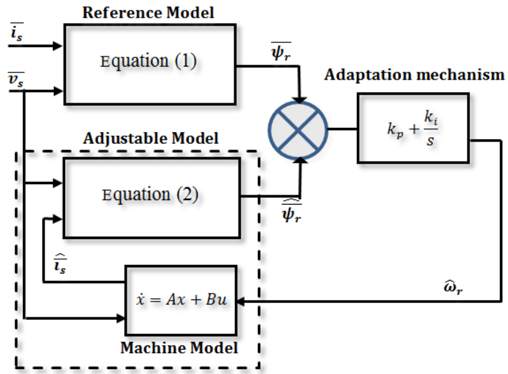

Fig. 2. Structure of the proposed MRAS

The current is estimated through the solution of machine state equations. The state space representation of induction motor in stationary reference frame is expressed in (3) and (4). The complete sensorless DTC for induction motor drives based on amplitude and angle control of stator flux is shown in Fig. 3.

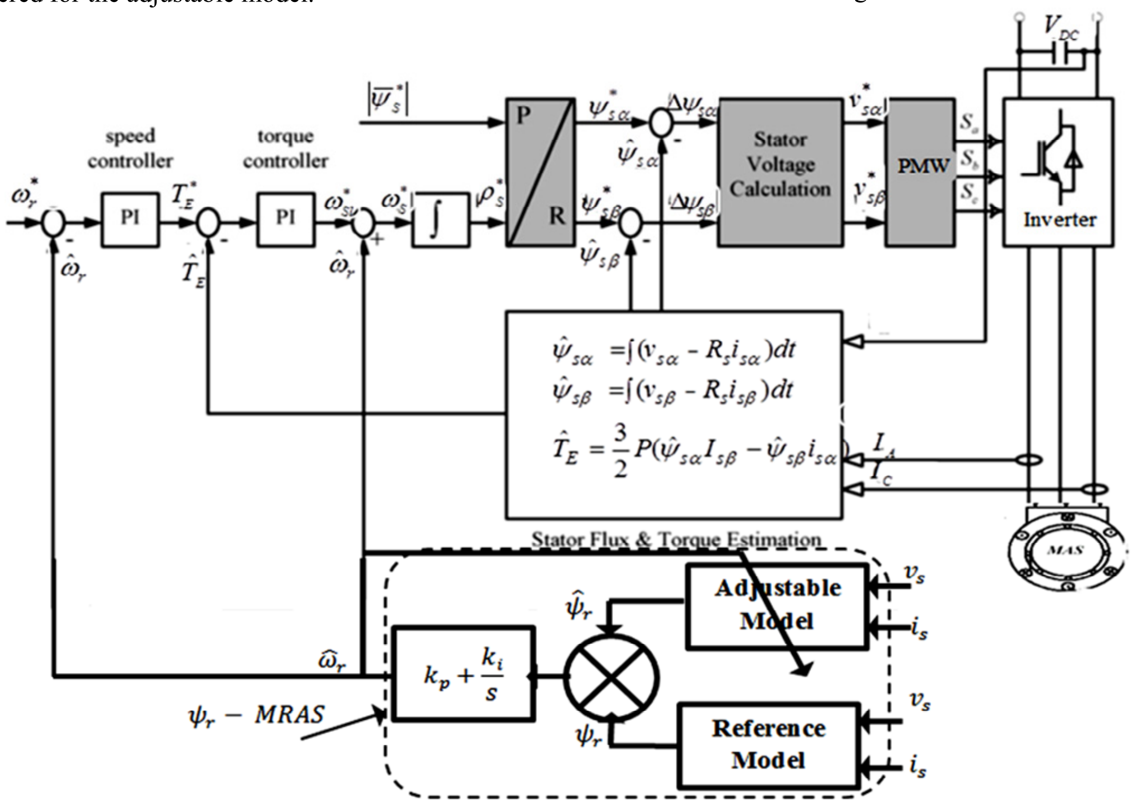

Fig. 3. Sensorless Direct Torque Control based on Amplitude and Angle control of Stator flux (DTC-AAS) with proposed speed estimator

$$\dot{\bar{\Psi}}_r = \frac{L_r}{L_m}\left(\bar{v}_s - R_s \bar{i}_s - \sigma L_s \dot{\bar{i}}_s\right); \tag{1}$$

$$\dot{\hat{\bar{\Psi}}}_r = \frac{L_r}{L_m}\left(\bar{v}_s - R_s \hat{\bar{i}}_s - \sigma L_s \dot{\hat{\bar{i}}}_s\right); \tag{2}$$

$$\frac{d}{dt}\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ \psi_{r\alpha} \\ \psi_{r\beta} \end{bmatrix} = \begin{bmatrix} -a_1 & 0 & a_2 & a_3\omega_r \\ 0 & -a_1 & -a_3\omega_r & a_2 \\ a_4 & 0 & -a_5 & -\omega_r \\ 0 & a_4 & \omega_r & -a_5 \end{bmatrix}\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ \psi_{r\alpha} \\ \psi_{r\beta} \end{bmatrix} + \frac{1}{\sigma L_s}\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \end{bmatrix}; \tag{3}$$

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ \psi_{r\alpha} \\ \psi_{r\beta} \end{bmatrix}, \tag{4}$$

where

$$a_1 = \frac{1}{\sigma L_s}\left(R_s + \frac{L_m^2}{L_r T_r}\right),\ a_2 = \frac{1}{\sigma L_s}\left(\frac{L_m}{L_r T_r}\right),$$

$$a_3 = \frac{1}{\sigma L_s}\left(\frac{L_m}{L_r}\right),\ a_4 = \frac{L_m}{T_r},\ a_5 = \frac{1}{T_r}$$

R_s, L_s, R_r, L_r are the resistances and cyclic inductances of stator and rotor respectively; $\bar{v}_s$, $\bar{i}_s$, $\bar{\psi}_r$ are the voltage, current vectors of stator and flux vector of rotor; L_m, ω_r are the mutual inductance and electric motor speed (or rotor frequency); $\sigma = 1 - L_m^2/L_sL_r$ is the motor dispersion coefficient.

PI design of MRAS-based speed estimator. It is important to design the adaptation mechanism of the MRAS according to the hyper-stability concept. This will result in a stable and quick response system where the convergence of the estimated value to the actual value can be assured with suitable dynamic characteristics. The induction machine model in the synchronously rotating (ω_{mr}) reference frame can be expressed as:

$$\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \\ \psi_{rd} \\ \psi_{rq} \end{bmatrix} = \begin{bmatrix} -a_1 & \omega_{mr} & a_2 & a_3\omega_r \\ -\omega_{mr} & -a_1 & -a_3\omega_r & a_2 \\ a_4 & 0 & -a_5 & \omega_{sl} \\ 0 & a_4 & -\omega_{sl} & -a_5 \end{bmatrix}\begin{bmatrix} i_{sd} \\ i_{sq} \\ \psi_{rd} \\ \psi_{rq} \end{bmatrix} + \frac{1}{\sigma L_s}\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix}; \quad (5)$$

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}\begin{bmatrix} i_{sd} \\ i_{sq} \\ \psi_{rd} \\ \psi_{rq} \end{bmatrix}. \quad (6)$$

Let us assume that $x = \begin{bmatrix} i_{sd} & i_{sq} & \Psi_{rd} & \Psi_{rq} \end{bmatrix}^T$; $u = \begin{bmatrix} v_{sd} & v_{sq} \end{bmatrix}^T$, $y = \begin{bmatrix} i_{sd} & i_{sq} \end{bmatrix}^T$, where v_{sd}, v_{sq}, i_{sd}, i_{sq} are the d-q components of stator voltage and currents respectively; Ψ_{rd}, Ψ_{rq} are the d-q components of rotor flux.

Therefore, in the state space form, (5) and (6) become,

$$\dot{x} = Ax + Bu; \quad (7)$$

$$y = Cx + Du. \quad (8)$$

The small signal representation of the above state space equations, described by (7) and (8) are:

$$\Delta\dot{x} = A\Delta x + \Delta A x_0; \quad (9)$$

$$\Delta y = C\Delta x, \quad (10)$$

or

$$\Delta y = C(SI - A)^{-1}\Delta A x_0, \quad (11)$$

where $x_0 = \begin{bmatrix} i_{sd0} & i_{sq0} & \Psi_{rd0} & \Psi_{rq0} \end{bmatrix}^T$ represents the operating point. The expression of ΔA is:

$$\Delta A = \begin{bmatrix} 0 & 0 & 0 & a_3 \\ 0 & 0 & -a_3 & 0 \\ a_4 & 0 & 0 & -1 \\ 0 & a_4 & 1 & 0 \end{bmatrix}\Delta\omega_r \quad (12)$$

and

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}. \quad (13)$$

From (11), using (12) and (13), the expression of Δy becomes:

$$\Delta y = \begin{bmatrix} \Delta i_{sd} \\ \Delta i_{sq} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}(SI - A)^{-1} \times \begin{bmatrix} 0 & 0 & 0 & a_3 \\ 0 & 0 & -a_3 & 0 \\ a_4 & 0 & 0 & -1 \\ 0 & a_4 & 1 & 0 \end{bmatrix}\begin{bmatrix} i_{sd0} \\ i_{sq0} \\ \psi_{rd0} \\ \psi_{rq0} \end{bmatrix}\Delta\omega_r. \quad (14)$$

Using (14), the transfer functions of $\Delta i_{sd}/\Delta\omega_r$ and $\Delta i_{sq}/\Delta\omega_r$ can be expressed as:

$$\frac{\Delta i_{sd}}{\Delta\omega_r} = \frac{(C_{14} - a_3 C_{12})\psi_{rd0}}{|SI - A|}; \quad (15)$$

$$\frac{\Delta i_{sq}}{\Delta\omega_r} = \frac{(C_{24} - a_3 C_{22})\psi_{rd0}}{|SI - A|}, \quad (16)$$

where

$$adj(SI - A) = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \\ C_{31} & C_{32} & C_{33} & C_{34} \\ C_{41} & C_{42} & C_{43} & C_{44} \end{bmatrix}. \quad (17)$$

Now, the error equation is:

$$\varepsilon = \overline{\psi}_r \otimes \hat{\overline{\psi}}_r = \psi_{rq}\hat{\psi}_{rd} - \hat{\psi}_{rq}\psi_{rd}, \quad (18)$$

where:

$$\psi_{rd} = \frac{L_r}{sL_m}(v_{sd} - (R_s + s\sigma L_s)i_{sd}); \quad (19)$$

$$\psi_{rq} = \frac{L_r}{sL_m}(v_{sq} - (R_s + s\sigma L_s)i_{sq}); \quad (20)$$

$$\hat{\psi}_{rd} = \frac{L_r}{sL_m}(v_{sd} - (R_s + s\sigma L_s)\hat{i}_{sd}); \quad (21)$$

$$\hat{\psi}_{rq} = \frac{L_r}{sL_m}(v_{sq} - (R_s + s\sigma L_s)\hat{i}_{sq}). \quad (22)$$

From (18), using (19) – (22), the error equation becomes:

$$\varepsilon = \frac{L_r(R_s + s\sigma L_s)}{sL_m}\left[v_{sq0}\left(i_{sd} - \hat{i}_{sd}\right) - v_{sd0}\left(i_{sq} - \hat{i}_{sq}\right) + \left(\hat{i}_{sd}i_{sq} - \hat{i}_{sq}i_{sd}\right)\right] \quad (23)$$

or

$$\varepsilon = \frac{L_r(R_s + s\sigma L_s)}{sL_m}\left[\left(v_{sq0}\Delta i_{sd} - v_{sd0}\Delta i_{sq}\right) + \left(\hat{i}_{sd}i_{sq} - \hat{i}_{sq}i_{sd}\right)\right] \quad (24)$$

For simplify the calculation, with the assumption of negligible the second term on the right-hand side of equation (24). With this assumption, the equation can be approximated as:

$$\varepsilon = \frac{L_r(R_s + s\sigma L_s)}{sL_m}\left(v_{sq0}\Delta i_{sd} - v_{sd0}\Delta i_{sq}\right). \quad (25)$$

The rotor flux error due to the small perturbation of rotor speed $\Delta\omega_r$ in the adjustable model can be expressed as:

$$\frac{\varepsilon}{\Delta\omega_r} = \frac{L_r(R_s + s\sigma L_s)}{sL_m}\left(v_{sq0}\frac{\Delta i_{sd}}{\Delta\omega_r} - v_{sd0}\frac{\Delta i_{sq}}{\Delta\omega_r}\right). \quad (26)$$

Putting the expressions of $\Delta i_{sd}/\Delta\omega_r$ and $\Delta i_{sq}/\Delta\omega_r$ (which are obtained from (15) and (16) respectively) into (26), the error transfer function becomes:

$$\frac{\varepsilon}{\Delta\omega_r} = \frac{\psi_{rd0}L_r(R_s + s\sigma L_s)}{sL_m}\left[\frac{v_{sq0}(C_{14} - a_3C_{12})}{|SI - A|} - \frac{v_{sd0}(C_{24} - a_3C_{22})}{|SI - A|}\right] = G_1(s). \quad (27)$$

Using the error transfer function (27), the closed loop block diagram of the MRAS is shown in Fig. 4. The closed loop transfer function between ω_r and $\hat{\omega}_r$ can be expressed as:

$$\frac{\omega_r}{\hat{\omega}_r}=\frac{G_1(s)\left(K_{Pmras}+\frac{K_{\mathrm{Im}ras}}{s}\right)}{1+G_1(s)\left(K_{Pmras}+\frac{K_{\mathrm{Im}ras}}{s}\right)}. \tag{28}$$

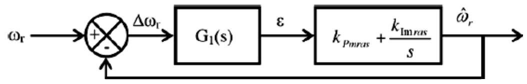

Fig. 4. Closed loop representation of the ψ_t^i MRAS based speed estimator

Improved rotor flux estimator. The drawbacks of the estimation of the rotor flux based on voltage model using open-loop integration as shown in (1) and (2) are DC drift and saturation problems. In this paper, improved rotor flux estimator by integrating algorithm with an amplitude limiter in polar coordinates is used to overcome the problems associated with the pure integrator [17-20]. The rotor flux estimator is shown in Fig. 5 is the limitation in Cartesian coordinates is performed as follows:

$$Z_L=\begin{cases}\sqrt{\lambda_\alpha^2+\lambda_\beta^2} & \text{if} \quad \sqrt{\lambda_\alpha^2+\lambda_\beta^2}<L;\\ L & \text{if} \quad \sqrt{\lambda_\alpha^2+\lambda_\beta^2}>L,\end{cases} \tag{29}$$

where Z_L is the output of the limiter; L is the limit value. L should be equal approximately to the stator flux reference. The limited components of the stator flux are then simply scaled with the ratio of the limited amplitude and unlimited amplitude:

$$Z_{\alpha L}=\frac{\sqrt{\lambda_\alpha^2+\lambda_\beta^2}}{Z_L}\lambda_\alpha; \quad Z_{\beta L}=\frac{\sqrt{\lambda_\alpha^2+\lambda_\beta^2}}{Z_L}\lambda_\beta, \tag{30}$$

where $Z_{\alpha L}$ and $Z_{\beta L}$ are the output limited values.

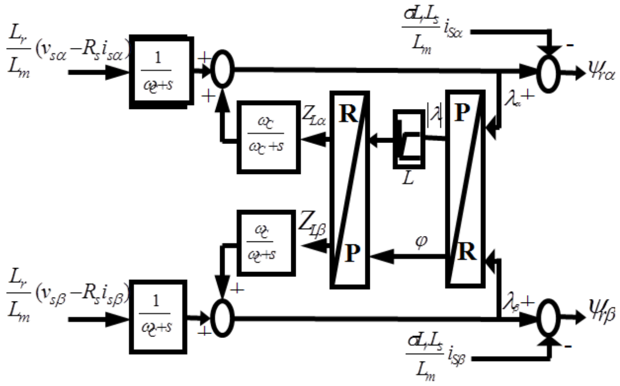

Fig. 5. Block diagram of the improved integrator algorithm with limited amplitude

Experimental setup. The experimental setup of the proposed control system is represented by the structure of the experimental setup shown in Fig. 6. It consists of a dSPACE DS1103 controller board with TMS320F240 slave processor, ADC interface board CP1103, a 4-pole induction motor with parameters listed in Table 1. A three-phase PMW inverter is connected to supply 500 V DC bus voltage, with the switching frequency and the dead time of 2 kHz and 70 µs, respectively.

The DS1103 board is installed in Pentium III 1.0 GHz PC for software development and results visualization. The control program is written in MATLAB/Simulink real time interface with sampling time of 100µs. A photograph of the experimental setup is shown in Fig. 7.

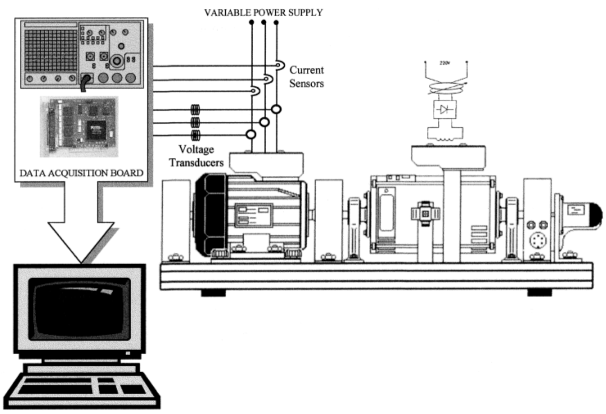

Fig. 6. Structure of the experimental setup

Table 1

Induction motor parameters

Parameter	Value
IM mechanical power P_n, kW	0.9
Nominal voltage V_n, V	220
Nominal current I_n, A	1.82
Nominal speed N, rpm	1400
Stator resistance R_s, Ω	12.75
Rotor resistance R_r, Ω	5.1498
Stator self-inductance L_s, H	0.4991
Rotor self-inductance L_r, H	0.4331
Mutual inductance L_m, H	0.4331
Moment of inertia J, kg·m^2	0.0035
Supply frequency f, Hz	50
Pole pairs number p	2

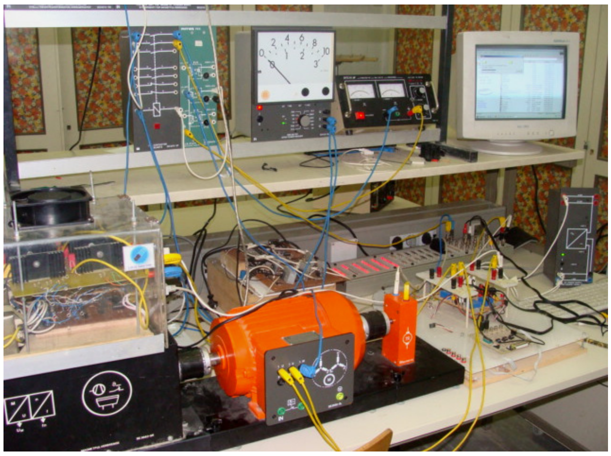

Fig. 7. View of the experimental setup

Experimental results. In the following tests, the estimated speed is used for speed control, where the drive is working as a sensorless DTC-AAS. The encoder speed is used for comparison purposes only. Selected experimental results for the tests are shown in the following section.

Test 1. Load torque rejection at 157 rad/s. This test examines the load torque disturbance rejection capability of the sensorless drive. Figure 8 shows in the (0 s ≤ t < 35 s) test between zero speed and 157 rad/s under a load torque from 11,5 s to 22 s. It can be observed that the rotor speed is not affected by the load torque change and the rotor speed error is small is available in Fig. 8,*a* and Fig. 8,*b*. It is found that the change in torque electromagnetic is shown in Fig. 8,*c*. The stator current is shown in Fig. 8,*d*, which follow the envelope of the load-torque. Some small stator flux oscillations can be observed but is maintained constant throughout the operation is available in Fig. 8,*e*.

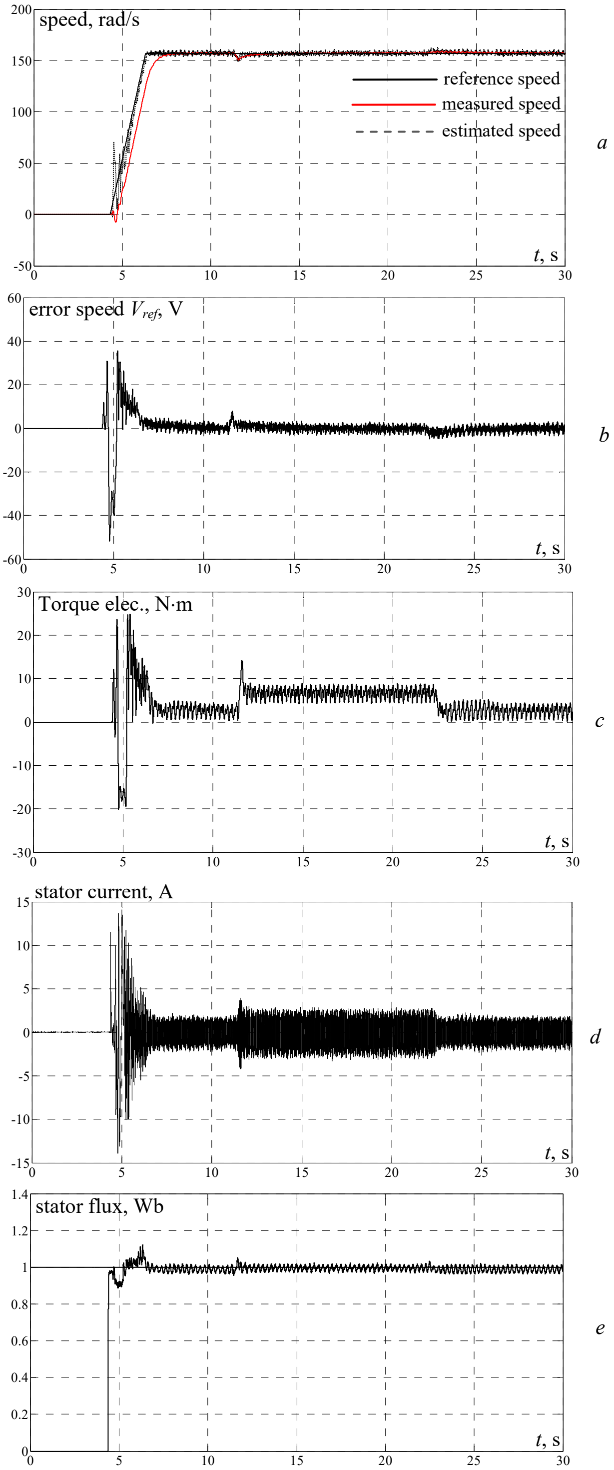

Fig. 8. Transient response for changing of load torque

Test 2. The speed reversal. The tracking performance of the sensorless drive is observed in Fig. 9 for a ramp speed command. Rotor reference speed is gradually increased from 0 to 157 rad/s during 2 s. Thereafter, the command speed is maintained constant at 50 rad/s up to 18.5 s. The speed reversal is taken place during 18.5-22.5 s. The rotor command speed is fixed to 157 rad/s after 22.5 s. The actual motor speed for such speed command is shown in Fig. 9,*a*. The speed estimation error is available in Fig. 9,*b*. It is noticed that the estimation error is small during steady state. The stator current increase during reversal operation is available in Fig. 9,*d*. Some small stator flux oscillations can be observed is shown in Fig. 9,*e*. The experimental results confirm that the proposed speed sensorless DTC for IM based on amplitude and angle control of stator flux method can satisfactorily estimate rotor speed and that it is possible to control the speed of an induction motor with the proposed method.

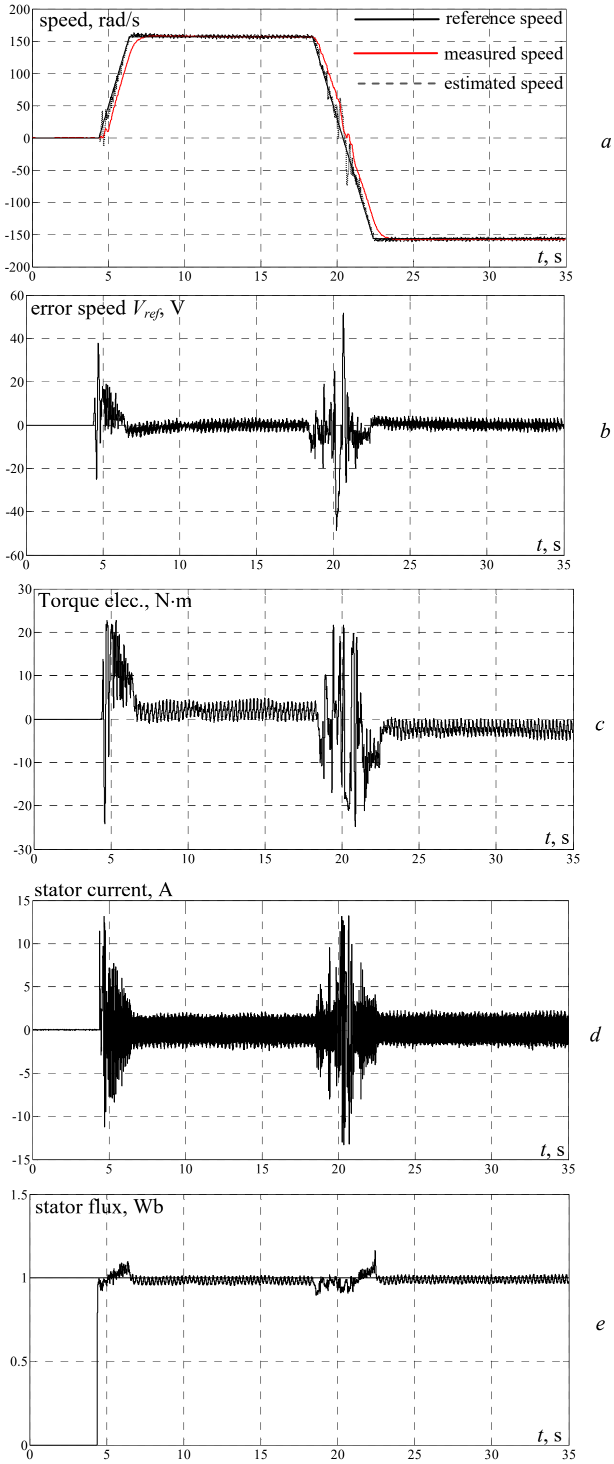

Fig. 9. Transient response for changing of reference speed

Conclusion. New speed estimation method for sensorless induction motor drive using model reference adaptive system has been presented in this paper. The model reference adaptive system is formulated with rotor flux. The algorithm needs the on-line solution of machine state equations. The realized estimator has used to perform the direct torque control for induction motor drives based on amplitude and angle. Experimental results for different speed profiles had shown. Although a small error and a small fluctuation are observed for the speed estimation, that the proposed new model reference adaptive system observer was able to estimate the actual speed. Thus the effectiveness of the proposed method of speed estimation is verified.

Conflict of interest. The author declares no conflict of interest.

REFERENCES

1. Maiti S., Chakraborty C. A new instantaneous reactive power based MRAS for sensorless induction motor drive. *Simulation Modelling Practice and Theory*, 2010, vol. 18, no. 9, pp. 1314-1326. doi: https://doi.org/10.1016/j.simpat.2010.05.005.

2. Chaabane H., Khodja D.E., Chakroune S., Hadji D. Model reference adaptive backstepping control of double star induction machine with extended Kalman sensorless control. *Electrical Engineering & Electromechanics*, 2022, no. 4, pp. 3-11. doi: https://doi.org/10.20998/2074-272X.2022.4.01.

3. Farhan A., Saleh A., Abdelrahem M., Kennel R., Shaltout A. High-Precision Sensorless Predictive Control of Salient-Pole Permanent Magnet Synchronous Motor based-on Extended Kalman Filter. *2019 21st International Middle East Power Systems Conference (MEPCON)*, 2019, pp. 226-231. doi: https://doi.org/10.1109/MEPCON47431.2019.9008188.

4. Ammar A., Kheldoun A., Metidji B., Ameid T., Azzoug Y. Feedback linearization based sensorless direct torque control using stator flux MRAS-sliding mode observer for induction motor drive. *ISA Transactions*, 2020, vol. 98, pp. 382-392. doi: https://doi.org/10.1016/j.isatra.2019.08.061.

5. Khamari D., Benlaloui I., Ouchen S., Makouf A., Drid S., Alaoui L.C., Ouriagli M. LPV Induction Motor Control with MRAS Speed Estimation. *2019 8th International Conference on Systems and Control (ICSC)*, 2019, pp. 460-464. doi: https://doi.org/10.1109/ICSC47195.2019.8950563.

6. Kumar R., Das S., Bhaumik A. Speed sensorless model predictive current control of doubly-fed induction machine drive using model reference adaptive system. *ISA Transactions*, 2019, vol. 86, pp. 215-226. doi: https://doi.org/10.1016/j.isatra.2018.10.025.

7. Xie H., Wang F., Zhang W., Garcia C., Rodriguez J., Kennel R. Predictive Field Oriented Control based on MRAS Current Estimator for IM Drives. *2020 IEEE 9th International Power Electronics and Motion Control Conference (IPEMC2020-ECCE Asia)*, 2020, pp. 1029-1032. doi: https://doi.org/10.1109/IPEMC-ECCEAsia48364.2020.9367976.

8. Guo X., Yin Z., Zhang Y., Bai C. Position sensorless control of PMLSM based on adaptive complex coefficient sliding mode observer. *Energy Reports*, 2022, vol. 8, pp. 687-695. doi: https://doi.org/10.1016/j.egyr.2022.02.271.

9. Babes B., Hamouda N., Kahla S., Amar H., Ghoneim S.S.M. Fuzzy model based multivariable predictive control design for rapid and efficient speed-sensorless maximum power extraction of renewable wind generators. *Electrical Engineering & Electromechanics*, 2022, no. 3, pp. 51-62. doi: https://doi.org/10.20998/2074-272X.2022.3.08.

10. Ankarao M., Kumar M.V., Dmesh P. Dynamic Performance Analysis of Reactive Power and Improved Rotor Flux Based MRAS for Induction Motor Drives Employing PI and Fuzzy Controller. *2018 2nd IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, 2018, pp. 892-896. doi: https://doi.org/10.1109/ICPEICES.2018.8897401.

11. Boukhechem I., Boukadoum A., Boukelkoul L., Lebied R. Sensorless direct power control for three-phase grid side converter integrated into wind turbine system under disturbed grid voltages. *Electrical Engineering & Electromechanics*, 2020, no. 3, pp. 48-57. doi: https://doi.org/10.20998/2074-272X.2020.3.08.

12. Agha Kashkooli M.R., Jovanovic M.G. Sensorless adaptive control of brushless doubly-fed reluctance generators for wind power applications. *Renewable Energy*, 2021, vol. 177, pp. 932-941. doi: https://doi.org/10.1016/j.renene.2021.05.154.

13. El Daoudi S., Lazrak L., El Ouanjli N., Ait Lafkih M. Sensorless fuzzy direct torque control of induction motor with sliding mode speed controller. *Computers & Electrical Engineering*, 2021, vol. 96, art. no. 107490. doi: https://doi.org/10.1016/j.compeleceng.2021.107490.

14. Zhang M., Cheng M., Zhang B. Sensorless Control of Linear Flux-Switching Permanent Magnet Motor Based on Improved MRAS. *2018 IEEE 9th International Symposium on Sensorless Control for Electrical Drives (SLED)*, 2018, pp. 84-89. doi: https://doi.org/10.1109/SLED.2018.8486093.

15. Fereka D., Zerikat M., Belaidi A. MRAS Sensorless Speed Control of an Induction Motor Drive based on Fuzzy Sliding Mode Control. *2018 7th International Conference on Systems and Control (ICSC)*, 2018, pp. 230-236. doi: https://doi.org/10.1109/ICoSC.2018.8587844.

16. Wang G., Zhang H. A new speed adaptive estimation method based on an improved flux sliding-mode observer for the sensorless control of PMSM drives. *ISA Transactions*, 2022, vol. 128, pp. 675-685. doi: https://doi.org/10.1016/j.isatra.2021.09.003.

17. Haider Khan M.S., Kumar Mallik S. Mechanical sensorless control of a rotor-tied DFIG wind energy conversion system using a high gain observer. *Journal of King Saud University - Engineering Sciences*. 2022, no. 04, pp. 1-9. doi: https://doi.org/10.1016/j.jksues.2022.05.005.

18. Khan Y.A., Verma V. Implementation of a new speed estimation technique for vector controlled switched reluctance machines. *Measurement*, 2022, vol. 198, art. no. 111315. https://doi.org/10.1016/j.measurement.2022.111315.

19. El Merrassi W., Abounada A., Ramzi M. Advanced speed sensorless control strategy for induction machine based on neuro-MRAS observer. *Materials Today: Proceedings*, 2021, vol. 45, pp. 7615-7621. doi: https://doi.org/10.1016/j.matpr.2021.03.081.

20. Laggoun Z.E.Z., Benalla H., Nebti K. A power quality enhanced for the wind turbine with sensorless direct power control under different input voltage conditions. *Electrical Engineering & Electromechanics*, 2021, no. 6, pp. 64-71. doi: https://doi.org/10.20998/2074-272X.2021.6.09.

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