Fuzzy Speed Sensorless Vector Control of Dual Star Induction Motor Drive Using MRAS Approach

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***Abstract*—This paper investigates a fuzzy speed sensorless vector control of Dual Star Induction Motor (DSIM) using MRAS approach. The rotor flux and speed estimator based on a PI model reference adaptive system (MRAS) is developed. The error in the instantaneous phase position of the two rotor flux estimates is utilized for rotor speed estimation. In order to achieve high performances in term of fast dynamic speed response and best disturbance rejection, fuzzy logic controller (FLC) is used for speed regulation. The proposed scheme is recommended for applications requiring robust speed control even in presence of some key parameters deviation. The performance of the suggested scheme has been tested through some simulation results.**

***Index Terms*—dual star induction motor, speed sensorless vector control, MRAS estimator, fuzzy logic controller**

I. Introduction

Due to its robustness, the simplicity of its structure, its low cost and which does not need a regular maintenance, the induction motor offers technological prospects in many industrial fields. Recently , there is an increasing interest towards multiphase motor drives, especially for medium and high power applications such as naval and railway propulsion systems. The use of multi-phase drives has been recognized as a viable approach to obtain high power ratings without increasing the stator current per phase, making it possible to use standard power switches based on a single device. Besides, multiphase motor drives possess several advantages over conventional three-phase motor drives, such as reducing the amplitude and increasing the frequency of torque pulsations, reducing the rotor harmonic currents, and improving the reliability and fault tolerance [1]-[3].

With the rapid development of microelectronics and power electronics, most adjustable-speed drives are now realized with ac machines. Vector control allows high-performance control of speed and torque to be achieved from an induction motor. A “speed sensor” is usually requisite for vector control.

All high-performance vector-controlled DSIM drives require accurate rotational speed or rotational position information for feedback control. This information is provided by an incremental encoder, which is the most common positioning transducer used today in industrial applications. The use of this sensor implies more electronics, higher cost, lower reliability, difficulty in mounting in some cases such as motor drives in harsh environment and high speed drives, increase in weight, increase in size, and increase electrical susceptibility [4]. Therefore, their elimination is an attractive prospect, which can be achieved by estimating speed from the stator terminal current measurements. This is what is commonly called the sensorless control of electrical machines.

In the existing literature, many approaches have been suggested for speed sensorless vector control induction motor drives. These methods are based on the following schemes [4]:

- Model Reference Adaptive System (MRAS) [5], [6];
- Extended Luenberger observers [7];
- Extended Kalman filter (EKF) [8];
- Instantaneous reactive power [4];
- Artificial neural network (ANN) [9];
- Harmonic caused by machine saliency [10];
- Carrier frequency signal injection in the stator windings [10].

This paper introduces a vector control based on a PI model reference adaptive system for dual star motor sensorless drives. The main advantages of MRAS scheme are less complex and more effective than any other estimation strategies [4], [5].

The aim of the work presented in this paper is: a) to present an estimation algorithm, which is able to obtain the accuracy of the speed estimation at low speeds range, b) to obtain high speed dynamic response the fuzzy logic controller FLC was used for speed regulation.

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The outline of this paper is as follows: in Section II, the modelling of DSIM is presented. Section III deals with the rotor field oriented control of a DSIM. The design of MRAS speed estimator is presented in Section IV. In Section V the conception of FLC for speed regulation is proposed. In Section VI, the performances of the proposed sensorless control are illustrated by some simulation results. Finally some concluding remarks are given in Section VII.

II. Dual Star Induction Motor Model

Under the assumptions of magnetic circuits linearity, and assuming sinusoidal distributed air-gap flux density, the equivalent two-phase model of DFIG motor, represented in a synchronous frame (d, q) and expressed in state-space form, is a fourth-order model [1]-[3]:

$$\dot{x} = Ax + Bv_s \tag{1}$$

where:

$$\begin{cases} X = \left[\psi_{ds1}\ \psi_{ds2}\ \psi_{qs1}\ \psi_{qs2}\ \psi_{dr}\ \psi_{qr}\right]^T; \\ U = \left[v_{ds1}\ v_{ds2}\ v_{qs1}\ v_{qs2}\ 0\ 0\right]^T \end{cases}$$

The system matrices are given by:

$$A = \begin{bmatrix} -\left(\frac{R_{s1}}{L_{s1}} - \frac{R_{s1}L_a}{L_{s1}^2}\right) & \frac{R_{s1}L_a}{L_{s1}L_{s2}} & W_s & 0 & \frac{R_{s1}L_a}{L_{s1}L_r} & 0 \\ \frac{R_{s2}L_a}{L_{s1}L_{s2}} & -\left(\frac{R_{s2}}{L_{s2}} - \frac{R_{s2}L_a}{L_{s2}^2}\right) & 0 & W_s & \frac{R_{s2}L_a}{L_{s2}L_r} & 0 \\ -W_s & 0 & -\left(\frac{R_{s1}}{L_{s1}} - \frac{R_{s1}L_a}{L_{s1}^2}\right) & \frac{R_{s1}L_a}{L_{s1}L_{s2}} & 0 & \frac{R_{s1}L_a}{L_{s1}L_r} \\ 0 & -W_s & \frac{R_{s2}L_a}{L_{s1}L_{s2}} & -\left(\frac{R_{s2}}{L_{s2}} - \frac{R_{s2}L_a}{L_{s2}^2}\right) & 0 & \frac{R_{s2}L_a}{L_{s2}L_r} \\ \frac{R_rL_a}{L_{s1}L_r} & \frac{R_rL_a}{L_rL_{s2}} & 0 & 0 & -\left(\frac{R_r}{L_r} - \frac{R_rL_a}{L_r^2}\right) & (W_s - W) \\ 0 & 0 & \frac{R_rL_a}{L_{s1}L_r} & \frac{R_rL_a}{L_rL_{s2}} & -(W_s - W) & -\left(\frac{R_r}{L_r} - \frac{R_rL_a}{L_r^2}\right) \end{bmatrix}$$

and:

$$B = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The mechanical modeling part of the system is given by:

$$J\frac{d\Omega_r}{dt} = T_{em} - T_l - k_f\Omega_r \tag{2}$$

Moreover, the electromagnetic torque is given by:

$$T_{em} = P\frac{L_m}{L_m+L_r}\left[\left(i_{qs1} + i_{qs2}\right)\psi_{dr} - \left(i_{ds1} + i_{ds2}\right)\psi_{qr}\right] \tag{3}$$

III. Rotor Field Oriented Control

According to the field orientation theory [3], [11], [12], the machine currents are decomposed into i_{sd} and i_{sq} components, which are respectively, flux and torque components. The key feature of this technique is to keep namely $\psi_{rq} = 0$ and $\psi_{rd} = \psi_r$. Hence, the flux and the electromagnetic torque are decoupled from each other, and can be separately controlled as desired. Then the drive behavior can be adequately described by a simplified model expressed by the following equations [3], [11], [12]:

$$T_{em} = p\frac{L_m}{(L_m+L_r)}\psi_r\left(i_{qs1} + i_{qs2}\right) \tag{4}$$

The expressions of the rotor currents may be given as:

$$i_{dr} = \frac{1}{L_r+L_m}\left[\psi_r - L_m\left(i_{ds1} + i_{ds2}\right)\right] \tag{5}$$

$$i_{qr} = -\frac{L_m}{L_r+L_m}\left(i_{qs1} + i_{qs2}\right) \tag{6}$$

Finally the sliding pulsation can be represented by:

$$w_{sl} = \frac{R_rL_m}{(L_m+L_r)}\frac{(i_{qs1}+i_{qs2})}{\psi_r} \tag{7}$$

IV. Design of MRAS Speed Estimator

The speed estimator, analyzed in this paper, is the one originally proposed in [5] and shown in Fig. 1, where the two left-hand side blocks perform integration of (1) and (2). It relies on measured stator currents and voltage. In the MRAS estimation method, there needs two models which outputs are to be compared. One is voltage model (or stator equation) and the other is current model (or rotor equation). Because the voltage model doesn't include rotor speed, it may be regarded as a reference and the other may be considered as an adjustable model, which includes rotor speed. [5], [6]. The error between two models can be used to derive a suitable adaptation law which generates the estimated rotor speed for the adjustable model rotor speed for the adjustable model.

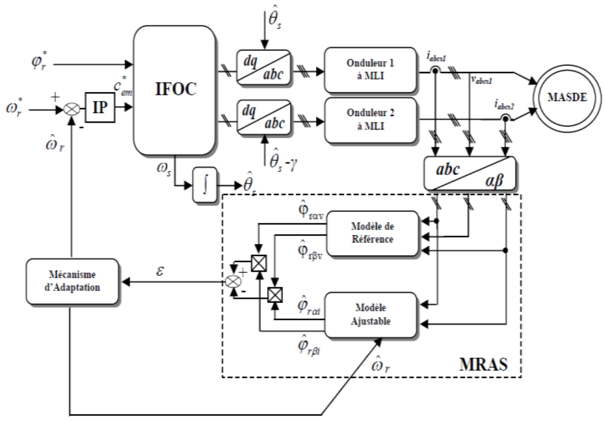


Figure 1. The block diagram of a fuzzy speed sensorless control of a field-oriented DSIM equipped with MRAS observer.

If we consider all of the parameters in the motor and the estimator are the same value, the estimator operates in the stationary reference frame (α, β) and it is described with the following equations [4]-[6]:

$$\frac{d\hat{\psi}_{r\alpha v}}{dt} = \frac{L_m+L_r}{L_m}\left[v_{s\alpha 1} - r_{s1}i_{s\alpha 1} - \delta(L_s + L_m)\frac{di_{s\alpha 1}}{dt} - \frac{L_m\,L_r}{L_m+L_r}\frac{di_{s\alpha 2}}{dt}\right]$$

$$\frac{d\hat{\psi}_{r\beta v}}{dt} = \frac{L_m+L_r}{L_m}\left[v_{s\beta 1} - r_{s1}i_{s\beta 1} - \delta(L_s + L_m)\frac{di_{s\beta 1}}{dt} - \frac{L_m\,L_r}{L_m+L_r}\frac{di_{s\beta 2}}{dt}\right] \tag{8}$$

with:

$$\delta = 1 - \frac{l_m^2}{(l_m + l_r)(l_m + l_s)}$$

$$\frac{d\hat{\psi}_{r\alpha i}}{dt} = \frac{L_m}{T_r}\left(i_{s\alpha 1} + i_{s\beta 1}\right) - \frac{1}{T_r}\hat{\psi}_{r\alpha i} - w_r\hat{\psi}_{r\beta i}$$

$$\frac{d\hat{\psi}_{r\beta i}}{dt} = \frac{L_m}{T_r}\left(i_{s\alpha 1} + i_{s\beta 1}\right) - \frac{1}{T_r}\hat{\psi}_{r\beta i} + w_r\hat{\psi}_{r\alpha i} \qquad (9)$$

In the above equations, (8) is the stator equation (or reference model) and (9) is the rotor equation (or adjustable model).

The error designed for regulator is expressed as follow:

$$\varepsilon = \hat{\psi}_{r\alpha i}\hat{\psi}_{r\beta v} - \hat{\psi}_{r\alpha v}\hat{\psi}_{r\beta i} \qquad (10)$$

The global stability of this algorithm is shown by Popv hyperstability criterion. By respecting Popov's criterion, Schauder proposes the following adaptation law [4]-[6]:

$$\widehat{w}_r = \varepsilon\left(k_p + \frac{k_i}{s}\right) \qquad (11)$$

As is evident from (8)-(11), the adaptive mechanism (PI controller in this case) relies on the error quantity that represents the difference between the instantaneous positions of the two rotor flux estimates.

The MRAS estimator gives the rotor flux amplitude $\hat{\psi}_r$ and its position needed for the field orientation, which is calculated as follow:

$$\hat{\rho} = \arctan\left(\frac{\hat{\psi}_{r\beta}}{\hat{\psi}_{r\alpha}}\right) \qquad (12)$$

V. Design of FLC for DSIM Speed Control

The structure of a standard FLC can be seen as a traditional PI controller, where the speed error e and its variation Δe are considered as input linguistic variables and the electromagnetic reference torque change ΔT_{em} is considered as the output linguistic variable [13], [14].

For convenience, the inputs and the output of the FLC were scaled with three different coefficients k_e, $k_{\Delta e}$, and $k_{\Delta Ten}$. These scaling factors can be constant or variable, and play an important role for the FLC design in order to achieve a good behaviour in both transient and steady state.

Seven membership functions with overlap, of triangular shape and equal width, are used for each input and output variable, so that a 49 rule base is created (see Fig. 2). The sum-product inference algorithm is selected to complete the fuzzy procedure, and the FLC output is obtained by the gravity center defuzzification method [15].

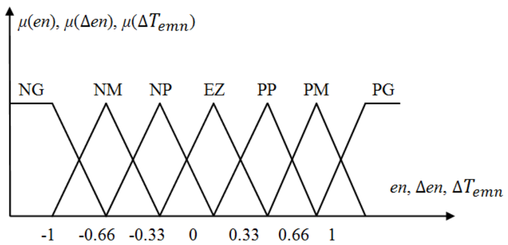


Figure 2. Membership functions of inputs and output of FLC.

The suggested built inference rules table used for FLC is depicted in Table I

TABLE I. Inference Rules Table

.Δe/e	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

where:

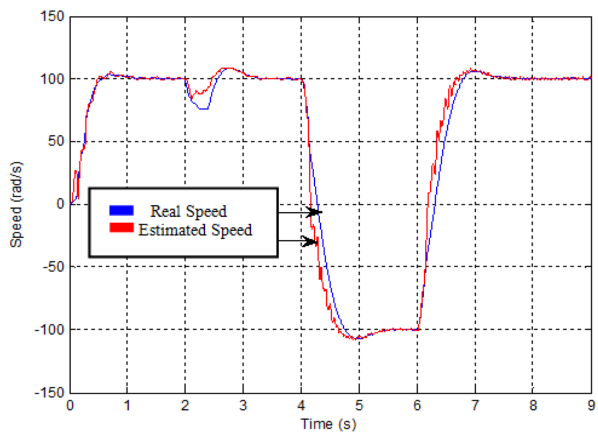
NB Negative Big;
NM Negative Medium;
NS Negative Small;
Z (Approximately) Zero;
PS Positive Small;
PM Positive Medium;
PB Positive Big.

VI. Simulation Results and Discussion

To investigate the effectiveness of the proposed system, and to check the closed-loop stability of the complete system, several tests were performed at different dynamic operating conditions such as sudden change in command speed, and step change in load. The parameters of the test motor are given in Table II.

TABLE II. DSIM Parameters

P_n	1.5 MW
V_n	220/380 V
P	2
R_{s1}, R_{s2}	3.72Ω
R_r	2.12 Ω
L_{s1}, L_{s2}	0.022H
L_r	0.006 H
L_m	0.3672 H
J	0.0662 kg m^2
K_f	0.001 N. m.s/rad



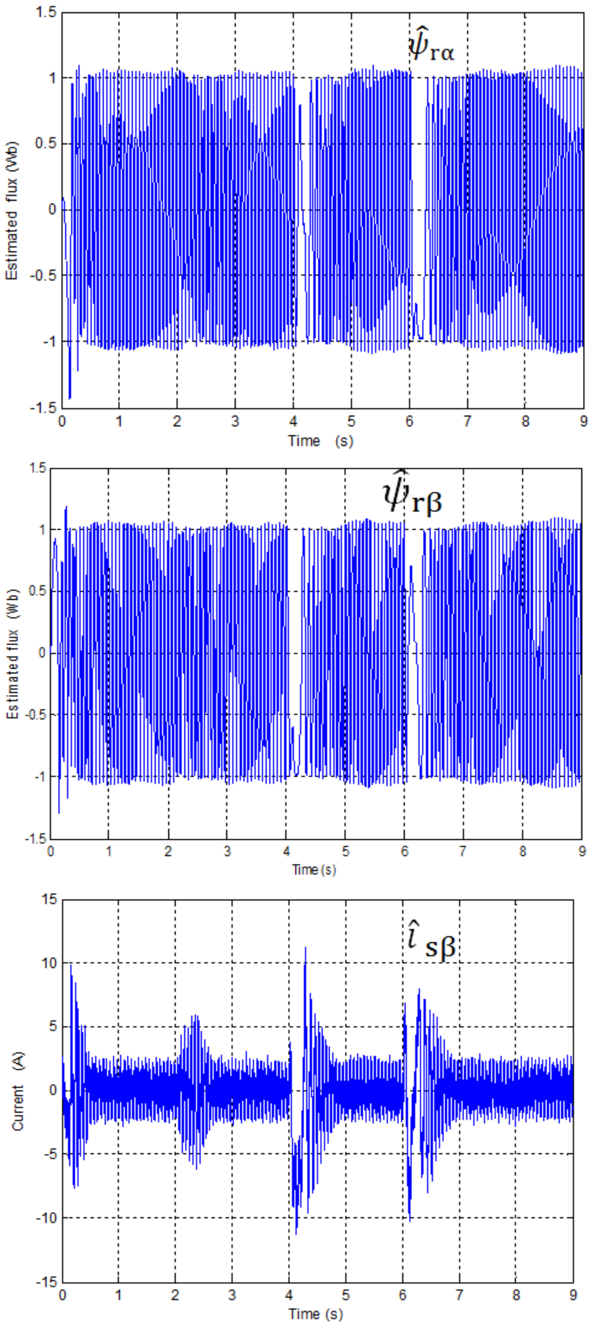


Figure 3. Transient response to speed step command ±100 (rad/s) at rated load.

Fig. 3 shows transient behavior of some characteristics of the drive with the following PI gains k_p = 20, k_i = 1455, Besides, the parameters of the FLC controller are: k_e = 280, $k_{\Delta e}$ = 0.5, $k_{\Delta Tem}$ = 0.95. One can notice the fast convergence of the estimated speed during the transients and the capability to maintain the estimation at standstill.

Besides, it can be seen that the dynamic and static performances are also satisfactory at the speed reversion.

The numerical tests at low speed have been also investigated at rated load (See Fig. 4), one can notice that the proposed estimator is still able to maintain estimates in those operating conditions and the dynamic behaviour is acceptable.

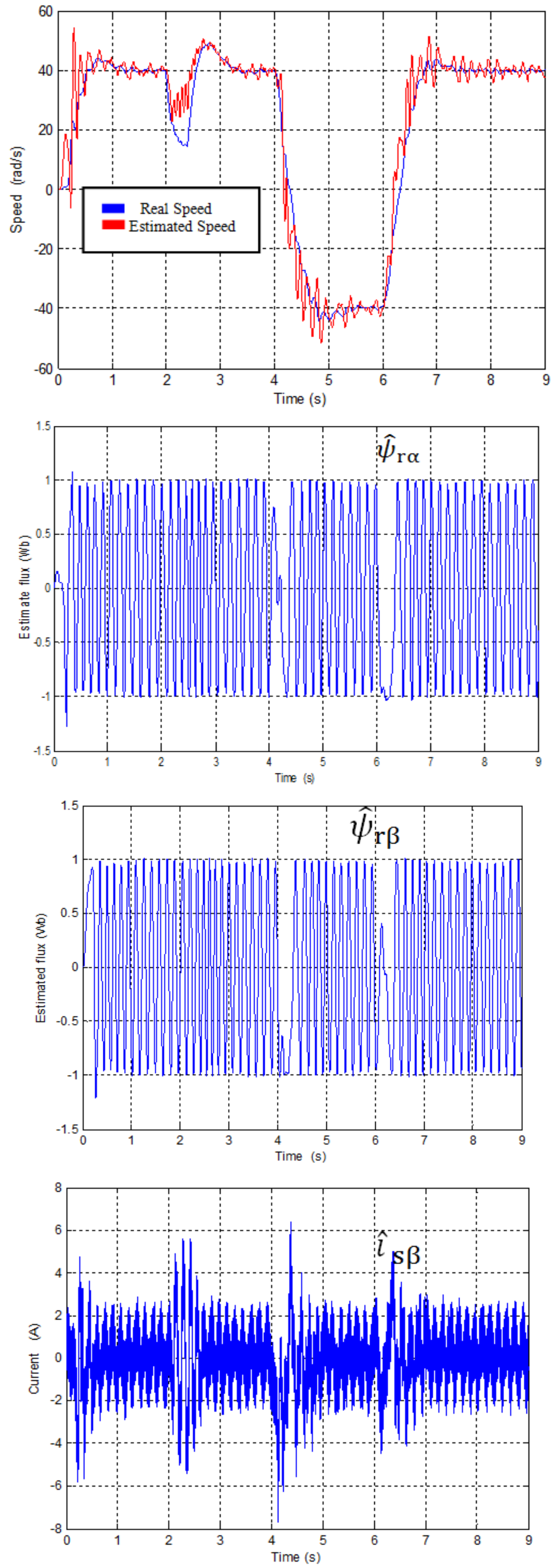


Figure 4. Transient response to speed step command ±40 (rad/s) at rated load.

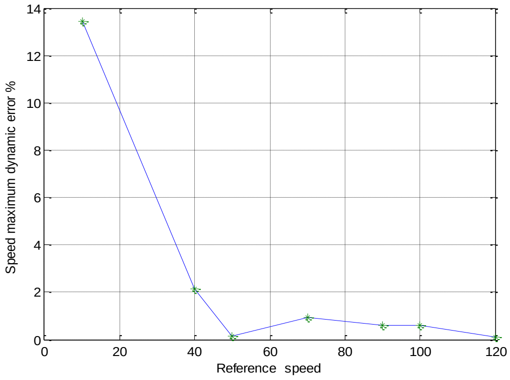


Figure 5. Speed maximum dynamic error at rated load operation versus reference speed.

The effectiveness of the sensorless scheme in terms of the speed estimation accuracy is also tested. Fig. 5 shows the maximum of the speed dynamic error versus the speed reference. It can be noted that the speed estimation is sufficiently accurate, in fact the dynamic error is 13% at a very low speed of (10 rad/s) and doesn't exceed 0.61% at the rated speed (100 rad/s).

VII. Conclusion

In this paper fuzzy speed sensorless vector control of dual star induction motor using a parallel MRAS estimator is presented. The error in the instantaneous phase position of the two rotor flux estimates is utilized for rotor speed estimation.

The effectiveness of the developed parallel MRAS structure is verified by simulation testing in the low speed region. From these simulation results, one can conclude that the proposed scheme shows good convergence and closed-loop stability over a wide speed range at rated load operation.

Appendix Nomenclature

ˆ	Estimated values
αβ	Stationary reference frame
$I_{qs1} I_{ds1}$ $I_{qs2} I_{ds2}$	dq stator current components
$\vec{\psi}_s$, $\vec{\psi}_r$	αβ rotor flux components
I_{qr} I_{dr}	"d-q" rotor currents
T_{em}	Electromagnetic torque
ω_{gl}	Sliding pulsation
δ	Stator leakage coefficient
ω_r , ρ	Rotor angular speed/ rotor flux angle
P_n	Nominal power
Ω_r	Mechanical speed of DSIM
R_{s1}, R_{s2}	Per phase stators resistances
L_{s1}, L_{s2}	Per phase stators leakages inductances
L_m	Magnetizing inductance
R_r	Per phase rotor resistance
L_r	Per phase rotor leakage inductances
K_f	Viscous coefficient
ω_s	Stator pulsation

References

[1] M. Mengoni, L. Zarri, A. Tani, G. Serra, and D. Casadei, "Sensorless multiphase induction motor drive based on a speed observer operating with third-order field harmonics," in *Proc. IEEE Energy Conversion Congress and Exposition (ECCE)*, 2011, pp. 68-74.

[2] A. Nanoty and A. R. Chudasama, "Control of designed developed six phase induction motor," *International Journal of Electromagnetics and Applications*, vol. 2, no. 5, pp. 77-84, 2012.

[3] F. Ameur and K. Kouzi, "Genetic algorithm optimized PI and fuzzy logic speed vector control of dual stator induction generator in wind energy conversion system," in *Proc 3rd International Conference on Systems and Control*, Algiers, Algeria, Oct. 29-31, 2013, pp. 174-180.

[4] M. Boussak and K. Jarray, "A high-performance sensor less indirect stator flux orientation control of induction motor drive," *IEEE Trans. Industry Elect.*, vol. 53, no. 1, pp. 41-49, Feb. 2006.

[5] C. Schauder, "Adaptive speed identification for vector control of induction motors without rotational transducers," *IEEE Trans. Ind. Appl.*, vol. 28, no. 5, pp. 1054-1061, 1992.

[6] L. Zhen and L. Xu, "Sensorless field orientation control of induction machines based on mutual MRAS scheme," *IEEE Trans. Ind. Electron.*, vol. 45, no. 5, pp. 824-831, Oct. 1998.

[7] L. B. Brahim, S. Tadakuma, and A. Akdag, "Speed control of induction motor without rotational transducers," *IEEE Trans. Ind. Appl.*, vol. 35, no. 4, pp. 844-850, 1999.

[8] Y. R. Kim, S. K. Sul, and M. H. Park, "Speed sensorless vector control of induction motor using an extended Kalman filter," *IEEE Trans. Ind. Appl.*, vol. 30, no. 5, pp. 1225-1233, 1994.

[9] S. H. Kim, T. S. Park, and G. T. Park, "Speed sensorless vector control of an induction motor using neural network estimation," *IEEE Trans. Power Electron.*, vol. 48, no. 3, pp. 609-614, Jun. 2001.

[10] D. Drevensek, D. Zarko, and T. A. Lipo, "A study of sensorless control induction motor at zero speed utilizing high frequency voltage injection," *EPE J.*, vol. 12, no. 3, pp. 7-11, Aug. 2003.

[11] R. Sadouni and A. Meroufel, "Performances comparative study of field oriented control (FOC) and direct torque control (DTC) of dual three phase induction motor (DTPIM)," *International Journal of Circuits, Systems and Signal Processing*, vol. 6, no. 2, 2012.

[12] H. Amimeur, D. Aouzellag, R. Abdessemed, and K. Ghedamsi, "Sliding mode control of a dual-stator induction generator for wind energy conversion systems," *ELSEVIER Trans, Electrical Power and Energy Systems*, vol. 42, no. 1, pp. 60-70, Nov. 2012.

[13] K. Kouzi, L. Mokrani, and M. S. Naït-Saïd, "A new design of fuzzy logic controller with fuzzy adapted gains based on indirect vector control for induction motor drive," in *Proc. The 35th Southeastern Symposium on System Theory*, Mar. 2003, pp. 362-366.

[14] K. Kouzi, L. Mokrani, and M. S. Naït-Saïd, "A fuzzy logic controller with fuzzy adapted gains based on indirect vector control for induction motor drive," *Journal of Electrical Engineering*, vol. 3, no. 2, pp. 49-54, 2003.

[15] Y. Shi. and P. C.Sen, "A new defuzzification method for fuzzy control of power converters," in *Proc. Conference Record of the 2000 IEEE Industry Applications Conference*, Rome, Italy, Oct. 2000, pp. 1202-1209.

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