SERBIAN JOURNAL OF ELECTRICAL ENGINEERING
Vol. 7, No. 1, May 2010, 41-55

UDK: 621.313.333:681.515

A Comparative Study of Field-Oriented Control and Direct-Torque Control of Induction Motors Using An Adaptive Flux Observer

Abdesselam Chikhi[1,a)], Mohamed Djarallah[1,b)], Khaled Chikhi[1,c)]

Abstract- This paper presents a comparative study of field-oriented control (IFOC) and direct-torque control (DTC) of induction motors using an adaptive flux observer. The main characteristics of field-oriented control and direct torque control schemes are studied by simulation, emphasizing their advantages and disadvantages. The performances of the two control schemes are evaluated in terms of torque, current ripples and transient responses to load toque variations. We can nevertheless observe a slight advance of DTC scheme compared to FOC scheme regarding the dynamic flux control performance and the implementation complexity. Consequently, the choice of one or the other scheme will depend mainly on specific requirements of the application.

Keywords: DTC, IFOC, Adaptive flux and speed observer, Sensorless control, Anti-windup PI.

1 Introduction

The fast development of power electronics and microelectronics has opened new issues of investigation for induction motor with vector control strategies [1, 2]. It is usually desirable that the motor can provide good dynamic torque response as that obtained from dc motor drives. Field-oriented control is a strategy research for induction motor speed adjustment feeding by variable frequency converter [3].

In Since its introduction in 1985, the direct torque control (DTC) [4, 5, 6], principle was widely used for induction motor drives with fast dynamics. Despite its simplicity, DTC is able to produce very fast torque and flux control, if the torque and the flux are correctly estimated, is robust with respect to motor parameters and perturbations.

[1]Department of Electrical Engineering, University of Batna, Chahid Med Boukhlouf, Batna 05000, Algeria;
E-mails: [a)]chikhi_aslem@yahoo.fr; [b)]djarmed@yahoo.fr; [c)]k_chikhi@lycos.com

Unlike field-oriented control (FOC), DTC does not require any current regulator, coordinate transformation and PWM signals generator; as a consequence, timers are not required. In spite of its simplicity, DTC allows obtaining a good torque control in steady-state and transient operating conditions. The problem is to quantify how good the torque control is with respect to FOC. In addition, this controller is very little sensible to the parameters detuning in comparison with FOC [6, 7].

In DTC, the flux is conventionally obtained from the stator voltage model, using the measured stator voltages and currents. This method, utilizing open-loop pure integration, suffers from increased noise on voltage and current and quantization errors in the digital system, in addition to the offset gain and conversions factors in the low speed range, even with the correct knowledge of the stator resistance. Aadaptive speed observer seems to be between the most promising methods, thanks to their good performances versus the computing time ratio. They have the advantage to provide both flux and mechanical speed estimates without problems of open-loop integration [8]. So, this paper is devoted to authenticate these discrepancies existing between IFOC and DTC control techniques.

2 Modelling of the Induction Motor

The induction motor is modelled in state space representation as follows:

$$\begin{cases} \dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{U} \\ \boldsymbol{y} = \boldsymbol{C}\boldsymbol{x} \end{cases} \tag{1}$$

where

$$\boldsymbol{x} = \begin{bmatrix} i_{s\alpha} & i_{s\beta} & \psi_{r\alpha} & \psi_{r\beta} \end{bmatrix}^T,$$

$$\boldsymbol{U} = \begin{bmatrix} V_{s\alpha} & V_{s\beta} \end{bmatrix}^T,$$

$$\boldsymbol{y} = \begin{bmatrix} i_{s\alpha} & i_{s\beta} \end{bmatrix}^T,$$

$$\boldsymbol{C} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}^T,$$

$$K = \left[\frac{M}{\sigma L_s L_r} \right],$$

$$\gamma = \left[\frac{R_s}{\sigma L_s} + \frac{R_r M^2}{L_r^2 \sigma L_s} \right]$$

$$A = \begin{bmatrix} -\gamma & 0 & \frac{K}{T_r} & K\omega_r \\ 0 & -\gamma & -K\omega_r & \frac{K}{T_r} \\ \frac{M}{T_r} & 0 & -\frac{K}{T_r} & -\omega_r \\ 0 & \frac{M}{T_r} & \omega_r & -\frac{K}{T_r} \end{bmatrix}, \quad B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}.$$

3 Principle of the DTC

DTC is a control philosophy exploiting the torque and flux producing capabilities of AC machines when fed by a voltage source inverter (VSI) that does not require current regulator loops. In the same time, it can achieve similar performance to that obtained from a vector control drive.

3.1 Stator flux and torque behaviors

In the (α, β) reference, the stator flux can be obtained by the following equation:

$$\overline{V}_s = R_s \overline{I}_s + \frac{\mathrm{d}}{\mathrm{d}t}\overline{\Psi}_s \ . \tag{2}$$

The electromagnetic torque is proportional to the vector product between the vector of stator and rotor flux according to the following expression [9, 10]:

$$C_e = k(\overline{\Psi}_s \times \overline{\Psi}_s) = k\,|\,\Psi_s\,||\,\Psi_r\,|\sin\delta\,, \tag{3}$$

with:

- $\overline{\Psi}_s$ – is the vector of stator flux;
- $\overline{\Psi}_r$ – is the vector of rotor flux;
- δ – is the angle between the vectors of stator and rotor flux.

3.2 Commutation strategy

In order to exploit the operation possible sequences of the inverter on two levels, the classical selection table of the DTC is summarised in **Table 1**. It shows the commutation strategy suggested by Takahashi [6], to control the stator flux and the electromagnetic torque of the induction motor. Fig. 1 gives the partition of the complex plan in six angular sectors $S_{I=1,2,\ldots,6}$. The basic sensorless DTC scheme for ac motor drives is show in Fig. 2.

4 Principle of IFOC

Fig. 3 shows a block diagram of the indirect field-oriented control system (IFOC or hysteresis FOC) for a sensorless induction motor [8].

The stator quadrature-axis reference is calculated from torque reference input Γ_e^* as [9, 10]:

Table 1
Selection table for direct torque control.

$\Delta\Psi_S$	1	1	1	0	0	0
$\Delta\Gamma_e$	1	0	-1	1	0	-1
S1	V2	V7	V6	V3	V0	V5
S2	V3	V0	V1	V4	V7	V6
S3	V4	V7	V2	V5	V0	V1
S4	V5	V0	V3	V6	V7	V2
S5	V6	V7	V4	V7	V0	V3
S6	V1	V0	V5	V2	V7	V4

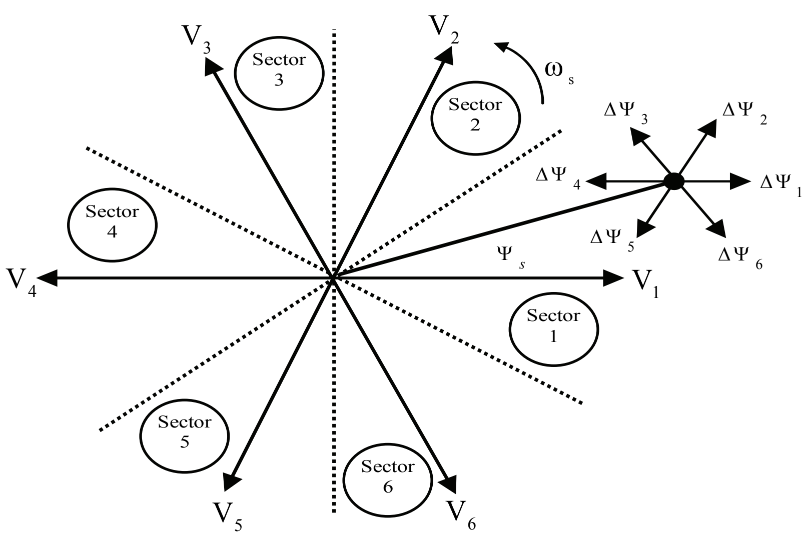

Fig. 1 – *Partition of the complex plan in six angular sectors* $S_{I=1,2,\ldots,6}$.

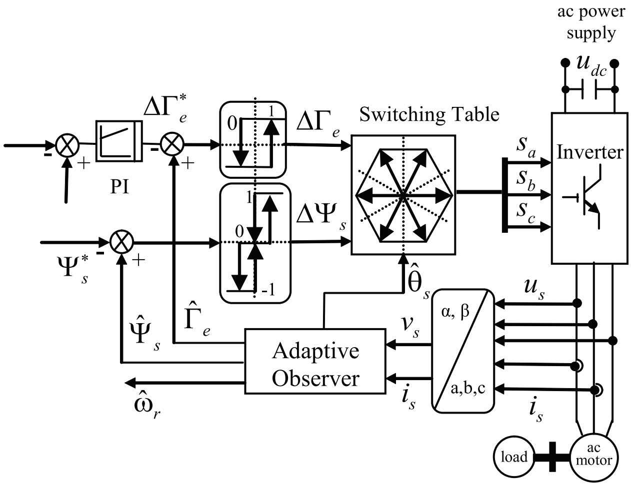

Fig. 2 – *Basic direct torque control for sensorless induction motor drives.*

$$i_{sq^*} = \frac{L_r}{pM}\left(\frac{\Gamma_e^*}{|\hat{\Psi}_r|}\right). \tag{4}$$

The estimated rotor flux linkage $|\hat{\Psi}_r|$ is given by:

$$\left|\hat{\Psi}_r\right| = \frac{M}{T_r s + 1} i_{sd} . \tag{5}$$

The stator direct-axis current reference is obtained from the rotor flux reference $|\Psi_r^*|$:

$$i_{sd}^* = \frac{\left|\Psi_r^*\right|}{M} . \tag{6}$$

The ω_s required for coordinates transformation is generated from the rotor speed w_r and slip frequency ω_{sl} :

$$\omega_s = \omega_{sl} + p\Omega_r . \tag{7}$$

The latter is obtained from the stator reference current i_{sq}^* :

$$\omega_{sl} = \frac{M}{\left|\hat{\Psi}_r\right|}\frac{1}{T_r} i_{sq}^* . \tag{8}$$

The current i_{sq}^* and i_{sd}^* are converted into phase current references i_a^*, i_b^*, i_c^*. The regulators process the measured and reference currents to produce the inverter gating signals s_a, s_b, s_c.

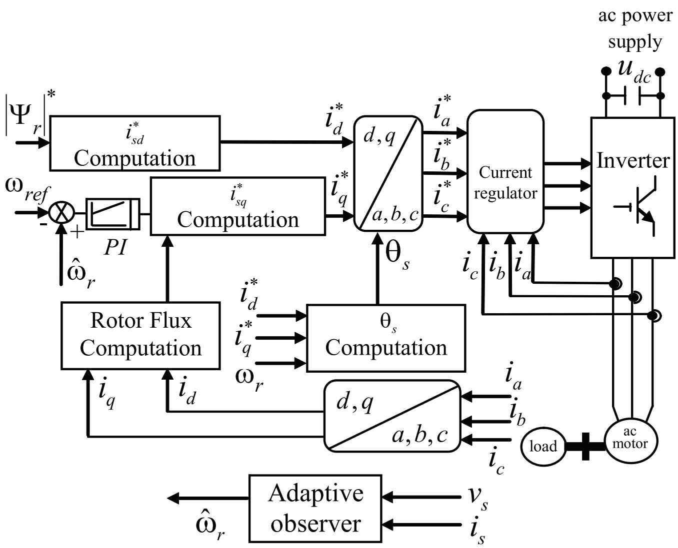

Fig. 3 – *Basic indirect field-oriented control for sensorless induction motor drives.*

5 Adaptive Flux and Speed Observer

By considering the mechanical speed as a constant parameter, a linear state observer for the stator flux can be derived as follows, [11, 12]:

$$\dot{\hat{\boldsymbol{X}}} = \boldsymbol{A}\hat{\boldsymbol{X}} + \boldsymbol{BU} + \boldsymbol{G}(\hat{i}_s - i_s) \ . \tag{9}$$

The symbol ^ denotes the estimated values and **G** is the observer gain matrix. By using an adaptation mechanism, we can estimate the rotor speed. The system states and the parameters can also be estimated. The speed adaptation mechanism is deduced by using a Lyapunov theory [13]. The estimation error of the stator current and the rotor flux represents the difference between the observer and the model of the motor. The dynamic error is given by:

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{e} = (\boldsymbol{A} + \boldsymbol{GC})\boldsymbol{e} + \Delta\boldsymbol{A}\hat{x} \ . \tag{10}$$

$$\Delta\boldsymbol{A} = \boldsymbol{A} - \hat{\boldsymbol{A}}\begin{bmatrix} 0 & 0 & 0 & pK\Delta\omega_r \\ 0 & 0 & -pK\Delta\omega_r & 0 \\ 0 & 0 & 0 & -p\Delta\omega_r \\ 0 & 0 & p\Delta\omega_r & 0 \end{bmatrix} . \tag{11}$$

We consider the following Lyapunov function,

$$V = \boldsymbol{e}^T \boldsymbol{e} + \frac{1}{\lambda}(\Delta w_r)^2 , \tag{12}$$

where λ is a positive constant, the derivative of Lyapunov function is giving by:

$$\frac{\mathrm{d}}{\mathrm{d}t} V = \boldsymbol{e}^T \left\{ (A(w_r) + GC)^T + (A(w_r) + GC) \right\} \boldsymbol{e} -$$
$$-2K \Delta w_r (e_1 \hat{x}_4 - e_2 \hat{x}_3) + \frac{2}{\lambda} \Delta w_r \dot{\hat{w}}_r .$$

From equation (13), we can deduce the adaptation law for the estimation of the rotor speed by the equality between the second and the third terms, we obtain:

$$\dot{\hat{\omega}}_r = \lambda K (e_1 \hat{x}_4 - e_2 \hat{x}_3) ,$$

with K is a positive constant.

To enhance the dynamic behavior of the speed observer, we have added a proportional term. The speed adaptation laws become**:**

$$\hat{\omega}_r = k_p (e_1 \hat{x}_4 - e_2 \hat{x}_3) + k_i \int_0^t (e_1 \hat{x}_4 - e_2 \hat{x}_3) \, \mathrm{d}t,$$

where k_p and k_i are positive gains.

6 Regulator Design

The transfer of the manipulated variable is affected by one or more nonlinear elements (hysteresis, saturation, etc.). The saturation of the manipulated variable can involve a phenomenon of racing of the integral action during the great variations (starting of the machine), which is likely to deteriorate the performances of the system or even to destabilize it completely.

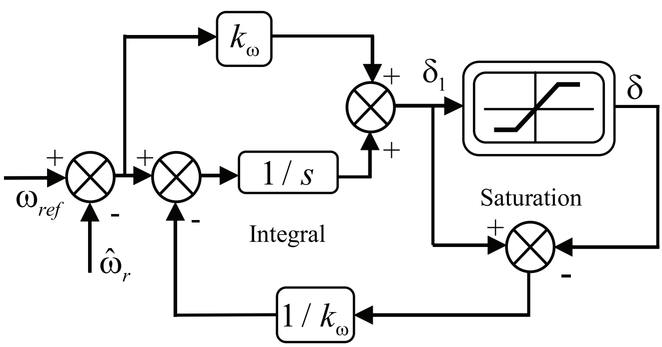

Fig. 4 – *Structure of the anti-windup* PI *system.*

To overcome this phenomenon, an adapted solution consists in correcting the integral action according to the diagram of the Fig. 4. The correction of the integral action is based on the difference between the values of (δ) upstream and downstream from the limiting device, balanced by the coefficient $1/k_{\omega}$ as given in [14, 15].

7 Simulation Results

A detailed comparison between the two techniques has been carried out by numerical simulations using Matlab/Simulink. In DTC system, the inverter voltage space vector directly controls torque and flux. Two independent hysteresis controllers are used to select appropriate stator voltage space vectors in order to maintain flux and torque between the upper and lower limits. The response time of hysteresis controllers is optimal but the switching frequency is variable. In IFOC, the estimated variable is the rotor speed. In order to show the performances and the robustness of DTC and IFOC, both techniques are analysed.

7.1 Comparison on the level of the regulation speed

Figs. 5a and 5b, show the settling performance comparison between the two techniques, DTC and IFOC. The DTC presents a high dynamics at starting instant and rapid load torque disturbance rejection without overshoot.

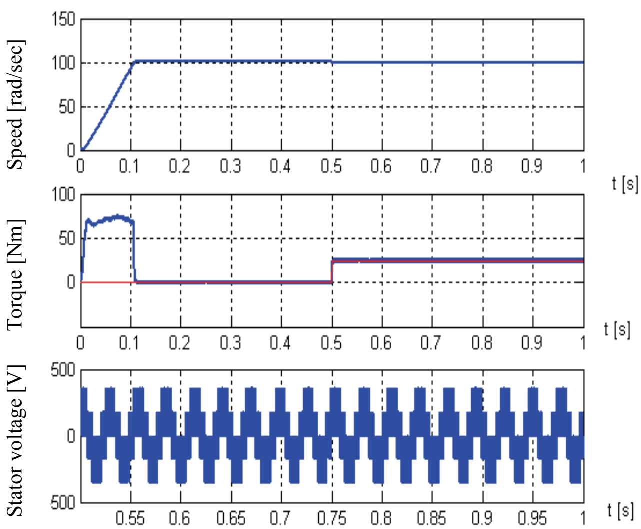

Fig. 5a – *Estimated speed, torque and stator voltage responses of* DTC *scheme.*

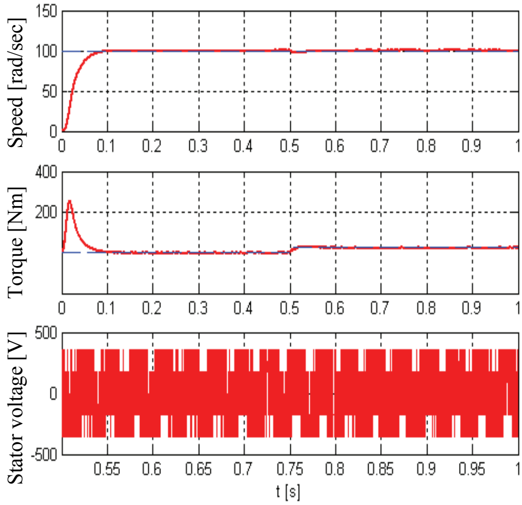

Fig. 5b – *Estimated speed, torque and stator voltage responses of* IFOC *scheme.*

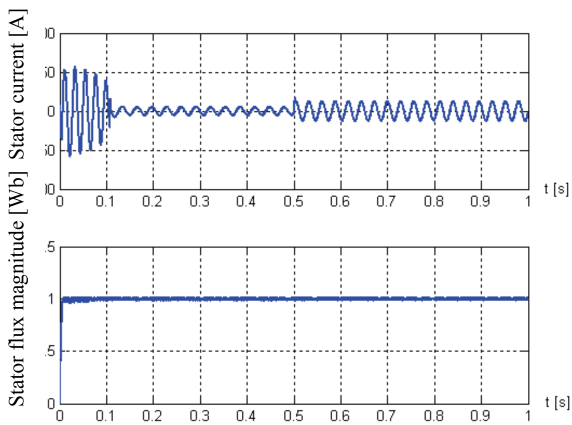

Fig. 6a – *Stator flux magnitude and stator current responses of* DTC *scheme.*

The same remarks can be observed for the responses of the stator flux magnitude show in Figs. 6a and 6b, where, one can observe an almost instantaneous establishment for the DTC compared to the IFOC, which improves moreover dynamics of the machine. The DTC presents a more oscillating current at starting. Indeed contrary to the IFOC which uses a regulation loop of the current. The DTC does not contain a current regulator loops.

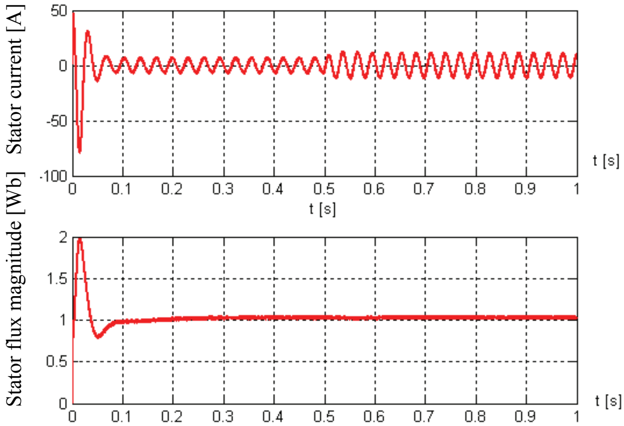

Fig. 6b – *Stator flux magnitude and stator current responses of* IFOC *scheme.*

7.2 Inversion of the speed

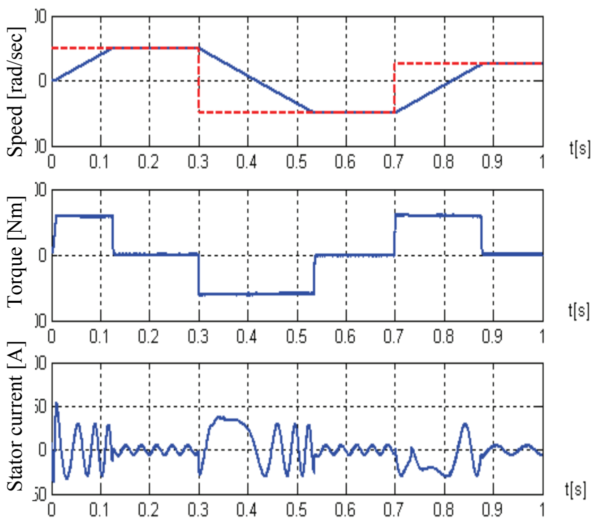

Fig. 7a – *Four quadrant speed estimation and torque and stator current responses of* DTC *scheme.*

The estimated speed, torque and the stator current waveform obtained with IFOC and DTC schemes are shown in Figs. 7a and 7b respectively. We applied a changing of the speed reference from –100 rad/s to 100 rad/s at $t = 0.3\,\text{s}$. It should be noted that the amplitude of the torque ripple in DTC is slightly higher than that of IFOC. However, the oscillations in IFOC scheme are more regular and uniform then the other one.

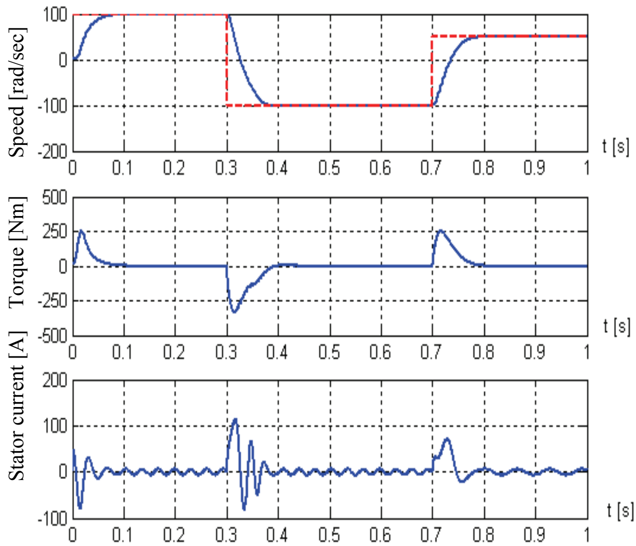

Fig. 7b – *Four quadrant speed estimation and torque and stator current responses of* IFOC *scheme.*

7.3 Variation of the load torques

The performance of the two schemes has been compared by analyzing the response to a step variation of the load torque from +25 Nm to –25 Nm (rated torque), between $t = 0.35\,\text{s}$ and $t = 0.7\,\text{s}$ after a leadless starting. Figs. 8a, 8b and 8c illustrate the torque responses, estimated speed and the stator current. We can see that the insensibility of the control algorithm to load torque variations in the case of DTC compared to the IFOC.

7.4 Effect of the stator resistance variation

To highlight the effect of the stator resistance variation in the case of DTC, the stator resistance variation carried out. The Figs. 9a and 9b illustrate the evolution of the stator flux magnitude with an increase of 100% of the stator resistance at $t = 0.5\,\text{s}$. We noted that, according to this result that the observer corrects well the stator flux magnitude and follows its reference in established mode.

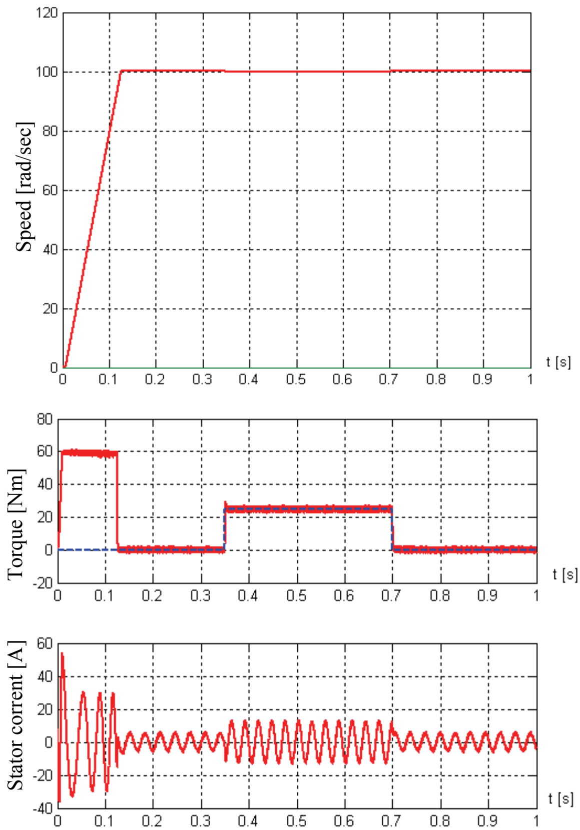

Fig. 8a – *Estimated speed, load torque and stator current responses of* DTC *scheme.*

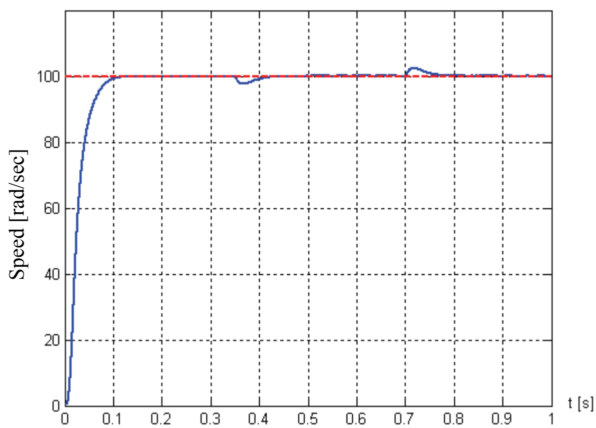

Fig. 8b – *Estimated speed for* IFOC *scheme.*

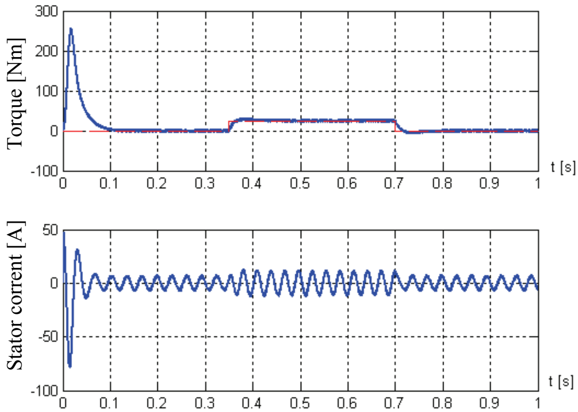

Fig. 8c – *Load torque and stator current responses* IFOC *scheme.*

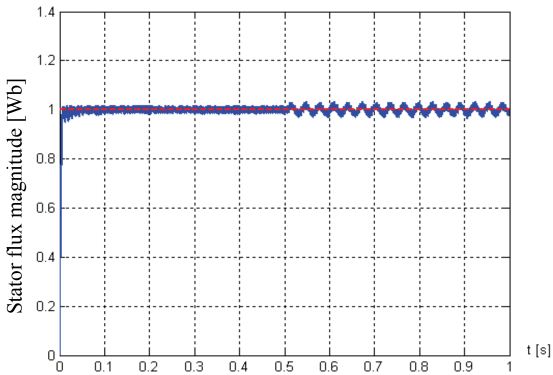

Fig. 9a – *Evolution of a real stator flux magnitude developed by the induction motor.*

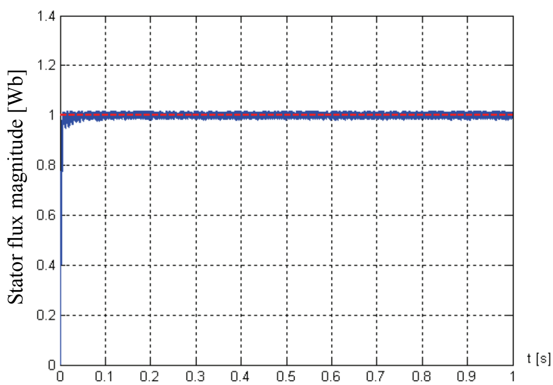

Fig. 9b – *Evolution of an estimated stator flux magnitude developed by the adaptive observer.*

8 Conclusion

The aim of this paper was to give a fair comparison between IFOC and DTC techniques. The synthesis of this simulation study reveals a slight advantage of DTC scheme compared to IFOC scheme regarding the dynamic flux control performance. The DTC might be preferred for high dynamic applications, but, shows higher current and torque ripple. The adaptive observer uses an adaptation mechanism for the speed estimation when the load torques change. This approach relies on the improvement of the components of stator flux. An anti-windup PI has been used to replace the classical PI controller in the speed control.

As a final conclusion, it seems that the use of anti-windup PI controller outperforms the classical PI controller in speed control of high performance induction motor drive.

We have given a general vision of an association adaptive observer-DTC, we can observe that the stator flux estimation by the adaptive observer with compensating fellows well the variation of stator resistance. This association makes more robust and more stable the induction motor based DTC.

9 Appendix

Both, the machine parameter and the PI regulator coefficient values used for the simulation are as follows:

Induction motor and PI regulator parameters	**Symbols**	**Values**
Stator resistance	R_s	1.2 Ω
Stator inductance	L_s	0.155 H
Rotor resistance	R_r	1.8 Ω
Rotor inductance	L_r	0.156 H
Mutual inductance	L_m	0.15 H
Moment of inertia	J	0.07kg/m^2
Number of pole pair	p	2
Proportional gain	k_p	2.5
Integral gain	k_i	52

10 References

[1] M. Kadjoudj, N. Golea, M.E. Benbouzid: Fuzzy Rule-based Model Reference Adaptive Control for PMSM Drives, Serbian Journal of Electrical Engineering, Vol. 4, No. 1, June 2007, pp.13 – 22.

[2] A. Ba-Razzouk, A. Cheriti, G. Olivier, P. Sicard: Field-oriented Control of Induction Motors using Neural-network Decouplers, IEEE Transaction on Power Electronics, Vol. 12, No. 4, July 1997, pp. 752 – 763.

[3] F. Blaschke: The Principle of Field Orientation as Applied to the New Transvector Closed Loop Control Systems for Rotating Machines, Siemens Review, Vol. 39, No. 5, 1972, pp. 217 – 220.

[4] Z. Sorchini, P. Krein: Formal Derivation of Direct Torque Control for Induction Machines, IEEE Transactions on Power Electronics, Vol. 21, No.5, September 2006, pp. 1428 – 1436.

[5] M. Vasudevan, R. Arumugam, S. Paramasivam: High-performance Adaptive Intelligent Direct Torque Control Schemes for Induction Motor Drives, Serbian Journal of Electrical Engineering, Vol. 2, No. 1, May 2005, pp. 93 – 116.

[6] I. Takahashi, T. Noguchi: A New Quick-response and High Efficiency Control Strategy of an Induction Machine, IEEE Transaction on Industry Application, Vol. 22, No. 5, Sep/Oct. 1986, pp. 820 – 827.

[7] T.A. Wolbank, A. Moucka, J.L. Machl: A Comparative Study of Field-oriented Control and Direct-torque Control of Induction Motors Reference to Shaft-sensorless Control at Low and Zero-speed, IEEE International Symposium on Intelligent Control, Oct. 2002, pp. 391 – 396.

[8] D. Casadei, F. Profumo, G. Serra, A. Tani: FOC and DTC: Two Viable Schemes for Induction Motors Torque Control, IEEE Transaction on Power Electronics, Vol. 17, No. 5, Sept. 2002, pp. 779 – 787.

[9] D. Telford, M.W. Dunnigan, B.W. Williams: A Comparison of Vector Control and Direct Torque Control of an Induction Machine, Power Electronics Specialist Conference, Vol. 1, June 2000, pp. 421 – 426.

[10] H. Le-Huy: Comparison of Field-oriented Control and Direct Torque Control for Induction Motors Drives, IEEE Industry Application Conference, Vol. 2, Oct. 1999, pp. 1245 – 1252.

[11] F. Khoucha, K. Marouani, K. Aliouane, A. Kheloui: Experimental Performance Analysis of Adaptive Flux and Speed Observers for Direct Torque Control of Sensorless Induction Motor Drives, Power Electronics Specialist Conference, Vol. 4, June 2004, Germany, pp. 2678 – 2683.

[12] J. Maes, J. Melkebeek: Speed Sensorless Direct Torque Control of Induction Motors using an Adaptive Flux Observer, Industry Application Conference, Vol. 4, Oct. 1999, pp. 2305 – 2312.

[13] K. Bousserhane, A. Hazzab, M. Rahli, B. Mazari, M. Kamli: Position Control of Linear Induction Motor using an Adaptive Fuzzy Integral – Backstepping Controller, Serbian Journal of Electrical Engineering, Vol. 3, No. 1, June 2006, pp. 1 – 17.

[14] Y. Cao, Z. Lin , D. G. Ward: An Anti-windup Approach to Enlarging Domain of Attraction for Linear Systems Subject to Actuator Saturation, IEEE Transaction on Automatic Control, Vol. 47, No. 1, Jan. 2002, pp. 140 – 145.

[15] L. Zaccarian, A.R. Teel: Nonlinear Scheduled Anti-windup Design for Linear Systems, IEEE Transaction on Automatic Control, Vol. 49, No. 11, Nov. 2004, pp. 2055 – 2061.