Sensorless Direct Torque Control of Induction Machine with MRAS Speed Estimator

Chiali El Mehdi, Massoum Ahmed[*], Meroufel Abdelkader, Guebli Abderrahmane

ICEPS Laboratory (Intelligent Control & Electrical Power Systems), Djillali Liabes University of Sidi Bel-Abbes. Sidi Bel-Abbes, Algeria

Abstract   The strategy of the DTC "direct torque control" is based on the separate control of the stator flux and electromagnetic torque using two hysteresis controllers and a switching table to generate directly the voltage inverter control associated with the induction motor. The rotor speed is estimated by the model reference adaptive system (MRAS) scheme which is determined from measured terminal voltages and currents. The MATLAB SIMULINK is used to perform the simulation.

Keywords   Direct Torque Control (DTC), Induction machine, MRAS, Sensorless

1. Introduction

Induction motors have become widely used in industry due to their simplicity of manufacture and maintenance. Currently, many industrial applications require control of speed, position and torque.

Recent advances in power semiconductor and microprocessor technology have made possible the application of advanced control techniques to alternating current (AC) motor drive systems.

In a perfect field oriented control, the decoupling characteristics of the flux and torque are affected highly by the parameter variation in the machine. One possible alternative to the vector control is the use of direct torque control (DTC) strategies with several advantages based on possible control directly the flux and the torque by selecting appropriate switching voltage vectors of the inverter. Direct Torque Control (DTC) has become a popular technique for the control of Induction Motor (IM) drives as it provides a fast dynamic torque response. This technique can be implemented easily using two hysteresis controllers and a Switching Table (ST) to select the switching voltage vector.

The controller receives the signals of rotor speed from the speed sensors. Unfortunately, the accuracy of the control system will decrease with the appearance of noises, causing low reliability. Furthermore, the conventional sensors make the higher cost; increase the complexity of the systems because of noise filtering.

Recently, many researchers have been carried out for the design of speed sensorless control schemes. In these new schemes the speed is obtained from the determined stator voltages and measured stator currents instead of using a sensor. The model reference adaptive system (MRAS) can overcome the necessity of the speed sensor an open loop and a close-loop[1], [2].

2. General Principles on Direct Torque Control

2.1. Model dedicated to the control (DTC)

The DTC is developed in the fixed coordinate system connected to the stator (α, β), we can write:

$$\overline{V}_s = R_s I_s + \frac{d\overline{\varphi}_s}{dt} \tag{1}$$

$$0 = R_r I_r + \frac{d\overline{\varphi}_r}{dt} - j\omega\overline{\varphi}_r \tag{2}$$

$$T_{em} = P \cdot (\overline{\varphi}_s \wedge \overline{I}_s) \tag{3}$$

The voltage vector Vs issued by a three-phase voltage inverter (Fig.1) is represented in theory by three Boolean variables control

S_j (j= a,b,c) such as:

S_j =1 : switch closed top and bottom switch open .

S_j =0 : Switch open top and bottom switch closed.

There are eight possible combinations of switches. From these combinations, we identify eight vectors voltages delivered by the inverter with six not zero $(\overline{V}_1,...,\overline{V}_6)$ and two are zero $(\overline{V}_0 \ et \ V_7)$.

2.2. Direct Control of Stator Flux Vector

The voltage vector is expressed by the following differential equation:

$$\overline{V}_s = R_s I_s + \frac{d\overline{\varphi}_s}{dt}$$

* Corresponding author:
moh_massoum@yahoo.fr (Massoum Ahmed)

This allows deducing the expression of stator flux by a simple integration.

$$\overline{\varphi}_s = \int (\overline{V}_s - R_s I_s) dt \tag{4}$$

During the switching interval, when stator resistance drop is neglected in high speed operating condition, the relationship between the voltage vectors and flux variation is given by:

$$\overline{\varphi}_S = \overline{\varphi}_{S0} + T_e \overline{V}_s \tag{5}$$

T_e : sampling period

Figure (1) shows that the amplitude of the stator flux vector $\overline{\varphi}_s$ is controllable by the voltage vector $\overline{V}_s$.
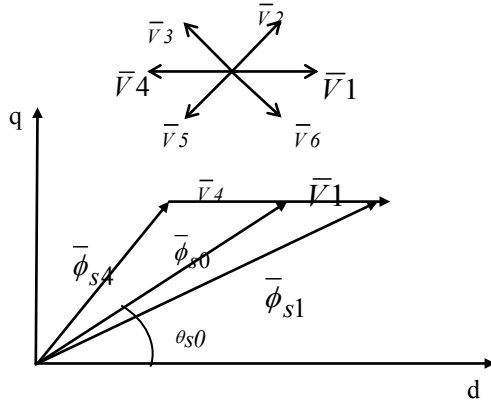

Figure 1. Influence of the choice of the voltage vector on stator flux vector

2.3. Electromechanical Torque Control

The electromagnetic torque is expressed in terms of the stator flux and rotor flux as follows[3], [4]:

$$T_{em} = K_c (\overline{\varphi}_s \times \overline{\varphi}_r) \tag{6}$$

Kc is a constant depending on the parameters of the machine.

$\overline{\varphi}_r$ is the rotor flux vector.

$$K_c = \frac{pM}{\sigma \cdot L_s \cdot L_r} \tag{7}$$

The stator flux and rotor flux can be written in the complex form:

$$\overline{\varphi}_s = [\varphi_s, \theta_s] = \varphi_s \cdot e^{j\theta_s}$$
$$\overline{\varphi}_r = [\varphi_r, \theta_r] = \varphi_r \cdot e^{j\theta_r}$$

The torque can be expressed as:

$$T_{em} = K_c \left\| \overline{\varphi}_s \right\| \cdot \left\| \overline{\varphi}_r \right\| \sin(\delta) \tag{8}$$

with $\delta = \theta_s - \theta_r$

δ is the angle between two vectors stator flux and rotor.

3. Description of the Direct Torque Control Structure
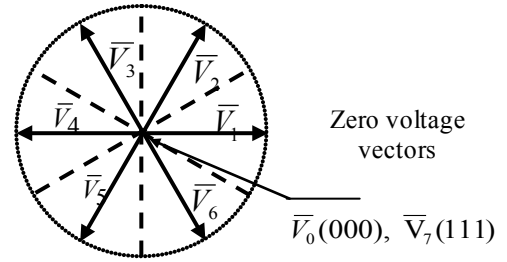
3.1. Estimated Stator Flux

Figure 2. vectors tensions and sectors of detection

The evolution of space $\overline{\varphi}_s$ in the database of Concordia (d, q) decomposes mainly into six sectors (Fig2).

Table 1. The switching table

flux φ	1	1	1	0	0	0
Torque T_{em}	1	0	-1	1	0	-1
S1	V2	V7	V6	V3	V0	V5
S2	V3	V0	V1	V4	V0	V6
S3	V4	V7	V2	V5	V0	V1
S4	V5	V0	V3	V6	V7	V2
S5	V6	V7	V4	V1	V0	V3
S6	V1	V0	V5	V2	V7	V4

To improve the DTC, the null vectors V_0 et V_7 are used, φ_s no longer rotates relative to the rotor.

The torque variation depends on the operating point of the machine in the torque-speed plan.

From the expression (5), we establish the expressions of two components of the stator flux in a reference frame related to the stator:

$$\overline{\varphi}_{ds} = \int (\overline{V}_{ds} - R_s I_{ds}) dt \tag{9}$$
$$\overline{\varphi}_{qs} = \int (\overline{V}_{qs} - R_s I_{qs}) dt$$

The module of the stator flux is written:

$$\varphi_s = \sqrt{\varphi_{ds}^2 + \varphi_{qs}^2} \tag{10}$$

Figure (3) shows that the modulus of the flow $\overline{\varphi}_s$ can be controlled in a way overall qualitative using a two level hysteresis comparator using the measured errors flow (εφs) at a given instant of operation.

$$\varepsilon_{\varphi s} = \varphi_{ref} - \varphi_s$$

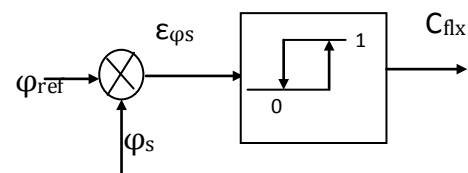with φ_{ref} : the modulus of the stator flux reference.

Figure 3. Principle of flux control with hysteresis φs

$$\left|\varphi_{ref}-\varphi\right| > \Delta\varphi \Rightarrow C_{flx}=1 \Rightarrow \varphi_{ref}>\varphi \Rightarrow \text{ Increase the}$$
flux.

$$\left|\varphi_{ref}-\varphi\right| < \Delta\varphi \Rightarrow C_{flx}=1 \Rightarrow \varphi_{ref}<\varphi \Rightarrow \text{ Decrease the}$$
flux.

3.2. Estimated Electromagnetic Torque

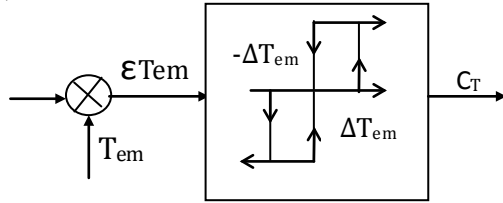In this case one uses a regulator hysteresis levels to three (Fig4)

Figure 4. Electromagnetic torque hysteresis

$$\left|T_{ref}-T_e\right| > \Delta T_e \Rightarrow C_T=1 \Rightarrow \text{ Increase the torque.}$$

$$\left|T_{ref}-T_e\right| < -\Delta T_e \Rightarrow C_T=-1 \Rightarrow \text{ Reduce the torque.}$$

$$\left|T_{ref}-T_e\right| < \Delta T_e \Rightarrow C_T=0 \Rightarrow \text{ Keep the constant}$$
torque

The stator flux and torque magnitudes are controlled by two independent hysteresis controllers. The selection of the appropriate voltage vector is based on the switching table given in Table 1.

4. Général Structure of Direct Torque Control
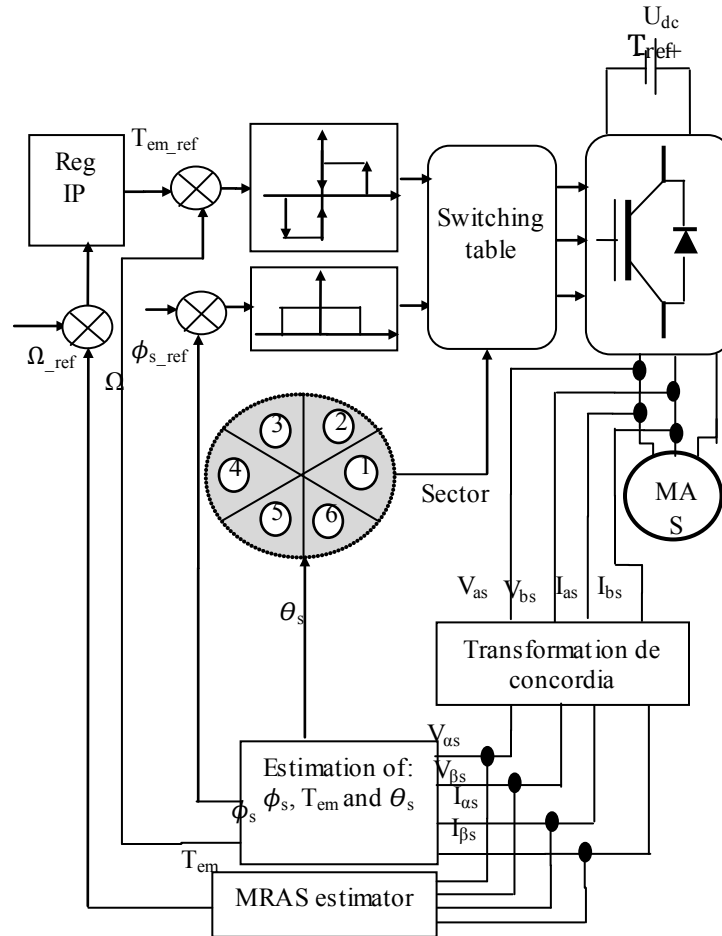
The structure of the control is shown in (Fig.5).

Figure 5. *DTC control structure* with MRAS speed estimator and IP regulator

5. Rotor Speed Estimation by MRAS Technique

Sensorless drives are becoming more and more important as they can eliminate the speed sensor maintaining accurate response. Monitoring only the stator current and stator voltages, it is possible to estimate the necessary control variables. The observer type used here is a MRAS. The basic scheme of the MRAS configuration is given in figure 6. The scheme consists of two models; reference and adjustable ones and an adaptation mechanism. The block "reference model" represents voltage model which is independent of speed. The block "adjustable model" is the current model which is using speed as a parameter. The block "adaptation mechanism" estimates the unknown parameter using the error between the reference and the adjustable models and updates the adjustable model with the estimated parameter until satisfactory performance is achieved. Since the MRAS is a close-loop system, the accuracy can be increased. However, the models contain pure integrators which cause estimation error due to unknown initial condition and estimation drift due to offset in the measured currents [1], [5].
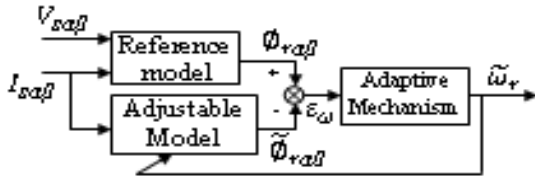

Figure 6. Block diagram of the MRAS estimator

5.1. Reference Model

The reference rotor flux components obtained from the reference model are given by:

$$\frac{d\varphi_{\alpha r}}{dt} = \frac{L_r}{L_m}\left(V_{\alpha s} - R_s I_{\alpha s} - \sigma L_s \frac{dI_{\alpha s}}{dt}\right) \quad (11)$$

$$\frac{d\varphi_{\beta r}}{dt} = \frac{L_r}{L_m}\left(V_{\beta s} - R_s I_{\beta s} - \sigma L_s \frac{dI_{\beta s}}{dt}\right) \quad (12)$$

5.2. Adaptive model

It explicitly depends on speed and will be constructed from equations of the machine rotor parameters:

$$\frac{d\varphi^*_{\alpha r}}{dt} = -\frac{1}{T_r}\varphi_{\alpha r} - p\Omega^*\varphi_{\beta r} + \frac{L_m}{T_r}I_{\alpha s} \quad (13)$$

$$\frac{d\varphi^*_{\beta r}}{dt} = -\frac{1}{T_r}\varphi_{\beta r} + p\Omega^*\varphi_{\alpha r} + \frac{L_m}{T_r}I_{\beta s} \quad (14)$$

5.3. Adaptation Mechanism

Finally the adaptation scheme generates the value of the estimated speed to be used in such a way as to minimize the error between the reference and estimated fluxes. In the classical rotor flux MRAS scheme, this is performed by defining a speed tuning signal ε_ω, to be minimized by a PI controller which generates the estimated speed which is fed back to the adaptive model. The expressions for the speed tuning signal and the estimated speed can be given as:

$$\varepsilon_\omega = (\phi_{r\beta}\tilde{\phi}_{r\alpha} - \phi_{r\alpha}\tilde{\phi}_{r\beta}). \quad (15)$$

$$\tilde{\omega}_r = k_p\varepsilon_\omega + k_i \int \varepsilon_\omega dt. \quad (16)$$

6. Simulation Results and Interpretations

The proposed scheme has been implemented with Matlab/Simulink in order to evaluate its performances.

Parameters of the induction machine:

P=1.5Kw, U=380V
N=1450tr/min, p=2
R_s=4.85Ω, R_r=3.81Ω
L_s=0.274H, L_r=0.274H, M=0.258H
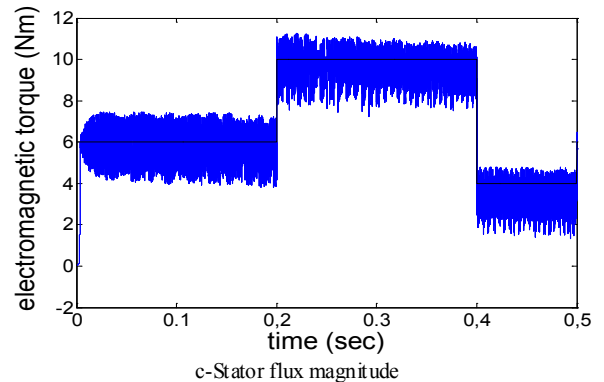J=0.031Kgm^2, f_r=0.0114Nm/rd/s

a-Flux trajectory
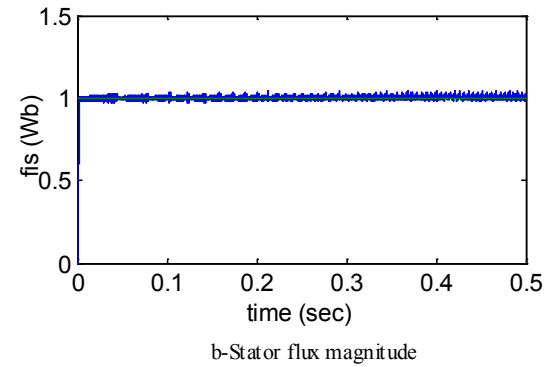

b-Stator flux magnitude
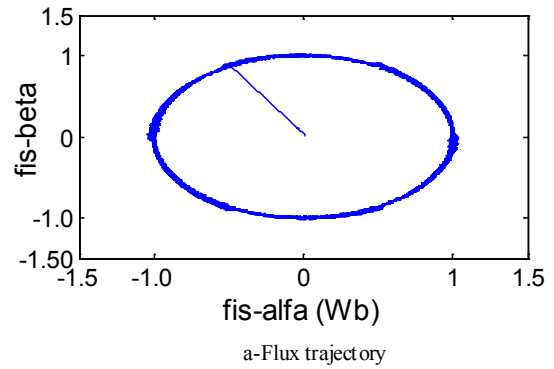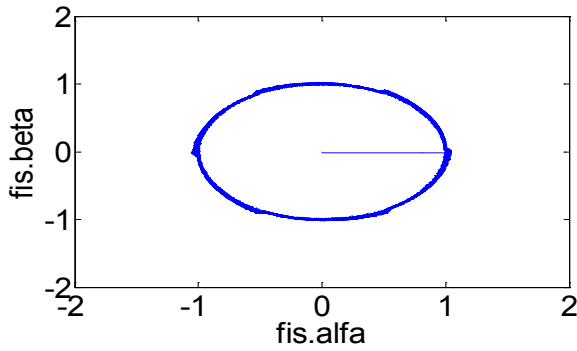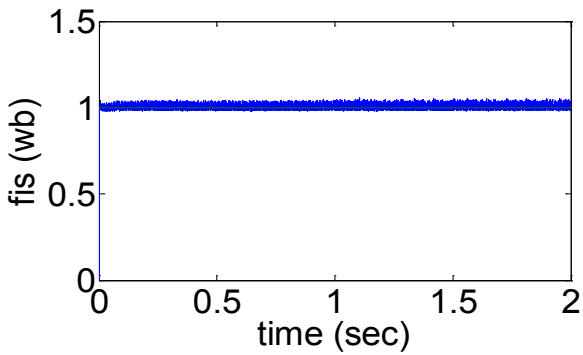

c-Stator flux magnitude

Figure 7. Responses of the system based on DTC technique

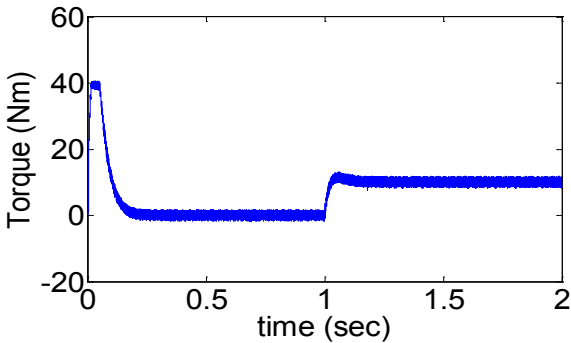The simulation results obtained in figure 8 shows the
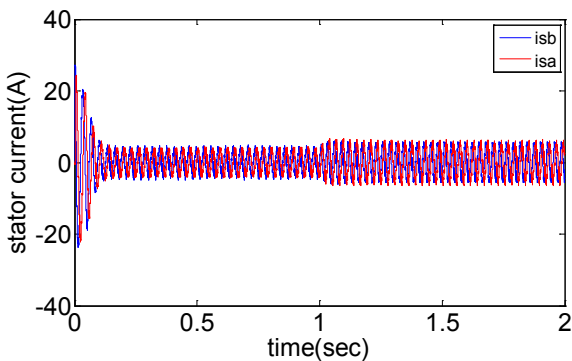
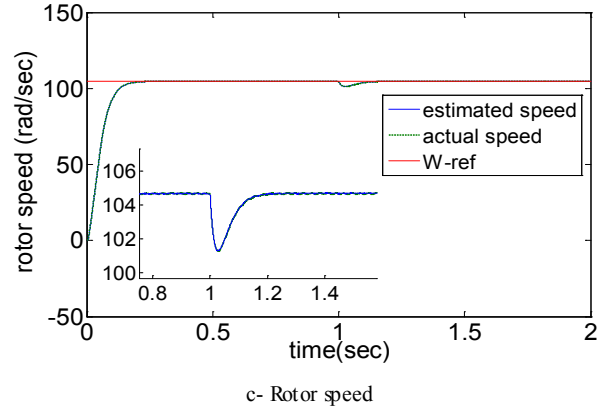behavior of the proposed MRAS speed estimator:

a-Flux trajectory

b-Stator flux magnetitude

c- Electromagnetic torque

c- Stator current

c- Rotor speed

Figure 8. DTC simulations with MRAS speed estimator

In the transient regime, the flux variations are faster than those of the torque, and when one reaches the steady state changes in torque and flux are limited by the hysteresis comparators.

Figure 8.c, represents the evolution of the electromagnetic torque versus time, we see that the torque quickly reaches the new reference.

The proposed speed estimator guarantees good rotor speed tracking, the disturbance rejection remains approximately 0.15s after the speed returns to its steady state with a regulator IP.

One can also observe the rapid establishment of the stator current during the transition phase.

From this analysis, the torque and flux present a high dynamic performances and good precision in steady state. It can be observed that the torque and flux are decoupled. The torque and the flux ripples are due to the hysteresis-band comparator.

7. Conclusions

The basic idea of the work that we presented was to analyse and see the performance of the DTC control without mechanical sensor.

The Direct Torque Control of an induction machine provides a satisfactory solution to the problems of robustness and dynamics encountered in control technology based on the orientation of the rotor flux.

In a DTC is preferable to work with a high frequency of the calculation to reduce torque oscillations caused by hysteresis controllers.

To speed up the response of the estimator it is important to choose Ki, we had better to increase the gain but not too much in order to ovoid an attenuation of noise at the input of the estimator.

REFERENCES

[1]   R.Toufouti , S.Meziane , H.Benalla , ''Direct torque control for induction motor using intelligent techniques'' Journal of theoretical and applied information technology, pp 35-44, JATIT,2007.

[2]   Badre Boussoufi , Mohammed Karim , Silviu Ionita , Ahmed Lagrioui , ''DTC control based artificial neural network for high performance PMSM drive'' Journal of theoretical and applied information technology,pp 165-176 2005-2011, JATIT & LLS .

[3]   ROBERTO Arnanz, LUIS J.Miguel, JOSE R. Peran, Antonio Mendoza, ''A modified direct torque control with fault tolerance'', control engineering practice 27/05/2011.

[4]   NABTI KHALIL ''contribution à la commande de la machine asynchrone par DTC et logique floue'' mémoire de magister en électrotechnique l'université de mentouri le 19/07/2006.

[5]   LOTFI BAGHLI ''contribution à la commande de la machine asynchrone, utilisation de la logique floue, des réseaux de neurone et des algorithmes génétiques'' thèse de doctorat en génie électrique l'université Henri Poincaré, Nancy le 14/01/1999.