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Performance Analysis of Field-Oriented Control and Direct Torque Control for Sensorless Induction Motor Drives

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Abstract: This study presents a contribution for detailed comparison between two sensorless control techniques for high performance induction motor drives: Field-Oriented Control (FOC) and Direct Torque Control (DTC). 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 and current ripples and transient responses to load toque variation. We can nevertheless say that the two control schemes provide in their basic configuration, comparable performances regarding the torque control and parameter sensitivity. We can note a slight advance of DTC scheme compared to FOC scheme regarding the dynamic flux control performance and the implementation complexity. The choice of one or the other scheme will depend mainly on specific requirements of the application.

Key words: DTC, FOC, IM, sensorless control, anti-windup PI

INTRODUCTION

In recent years, several studies have been developed which propose alternative solutions to the FOC control of a PWM inverter-fed motor drive with two objectives: first, achievement of an accurate and fast response of the flux and the torque and second, reduction in the complexity of the control system. Among the various proposals, Direct Torque and Flux Control (DTFC) also called Direct Torque Control (DTC), has found wide acceptance, (Blaschke, 1972).

Since its introduction in 1985, the direct torque control (DTC) (Lascu, *et al*., 2000), principle was widely used for IM 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.

Unlike 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 a good torque control in steady-state and transient operating conditions to be obtained. 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, (Takahashi and Noguchi, 1986).

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.

MODELING OF THE INDUCTION MOTOR

In this study, the induction motor model is expressed as follow:

$$\begin{cases} \dot{x} = Ax + BU \\ y = Cx \end{cases} \tag{1}$$

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

$$U = \begin{bmatrix} V_{sa} & V_{sß} \end{bmatrix}^T, \quad y = \begin{bmatrix} i_{sa} & i_{sß} \end{bmatrix}^T$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}^T K = \left[\frac{M}{\sigma L_s L_r} \right]$$

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

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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 that does not require current regulator loops, still attaining similar performance to that obtained from a vector control drive.

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

$$\bar{V}_s = R_s \bar{I}_s + \frac{d}{dt} \bar{\Psi}_s \qquad (2)$$

Behavior of the torque: The electromagnetic torque is proportional to the vector product between the vector of stator and rotor flux according to the following expression, (Balkacem *et al.*, 2005; Telford *et al.*, 2000):

$$C_e = k(\bar{\psi}_s \times \bar{\psi}_s) = k\left|\psi_s\right|\left|\psi_r\right|\sin(\delta) \qquad (3)$$

with:

- $\bar{\psi}_s$: is the vector of stator flux;
- $\bar{\psi}_r$: is the vector of rotor flux;
- δ : is the angle between the vectors of stator and rotor flux .

Development of the 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 and Noguchi (1986), to control the stator flux and the electromagnetic torque of the induction motor. Figure 1 gives the partition of thecomplex plan in six angular sectors SI = 1… 6.

The basic sensorless DTC scheme for ac motor drives is show in Fig. 2.

IFOC PRINCIPLE

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

The stator quadrature-axis reference is calculated from torque reference input Γ^*_e as (Telford *et al.*, 2000; Hoang, 1999):

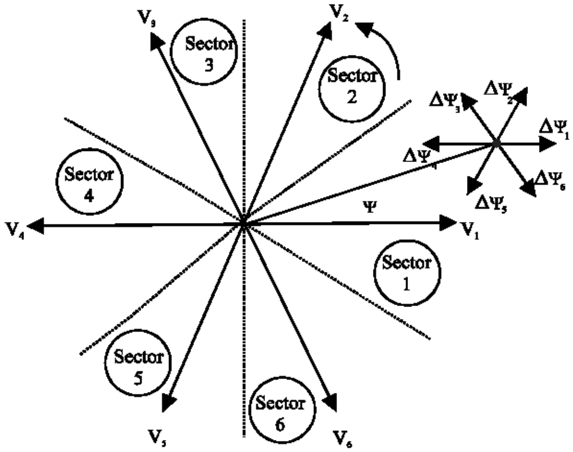

Fig. 1: Partition of the complex plan in six angular sectors $S_{I=1\ldots6.}$

Table 1: Selection table for direct torque control

$\Delta\Psi_s$	$\Delta\Gamma_e$	S_1	S_2	S_3	S_4	S_5	S_6
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_7	V_0	V_7	V_0	V_7	V_0
	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_5	V_6	V_1	V_2	V_3	V_4

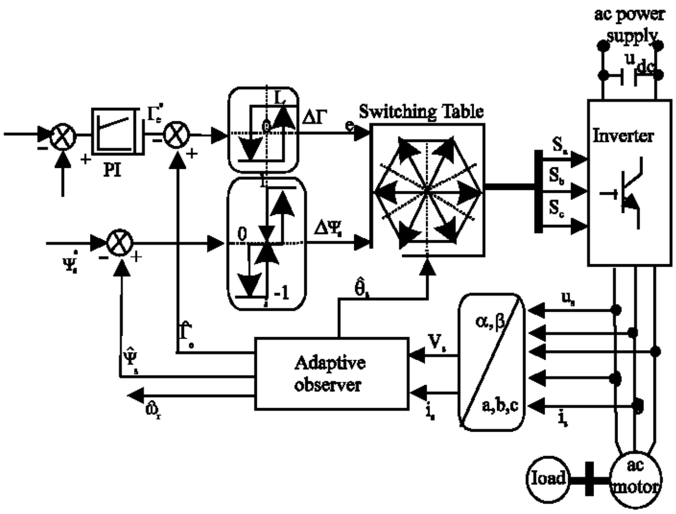

Fig. 2: Basic direct torque control for sensorless induction motor drives

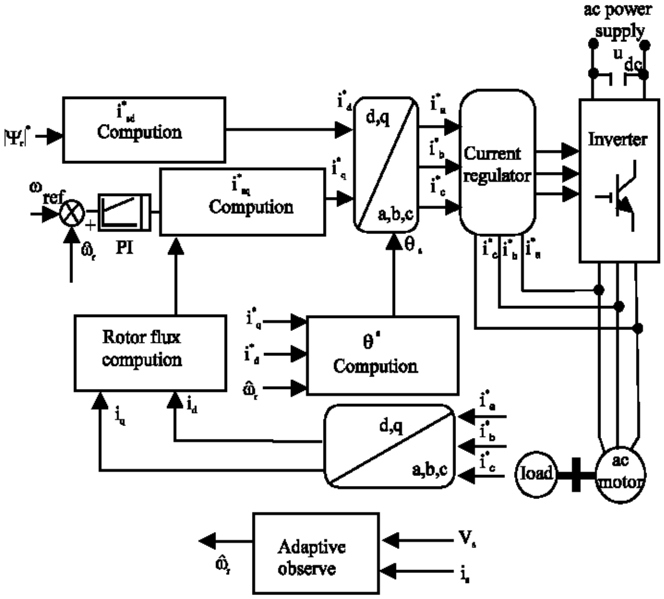

Fig. 3: Basic indirect field-oriented control for sensorless induction motor drives

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

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

$$|\hat{\psi}_r| = \frac{M}{T_r s + 1} i_{sd} \qquad (5)$$

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

$$i_{sd}^{*} = \frac{|\psi_r^*|}{M} \qquad (6)$$

The $\omega_s$required for coordinates transformation is generated from the rotor speed and slip frequency:

$$\omega_s = \omega_{sl} + p\Omega_r \qquad (7)$$

The latter is obtained from the stator reference current i^*_{sd}:

$$\omega_{sl} = \frac{M}{|\hat{\psi}_r|}\frac{1}{T_r} i_{sq}^{*} \qquad (8)$$

The current I^*_{sd} and 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.

ADAPTIVE FLUX AND SPEED OBSERVER

A linear state observer for the stator flux can be derived as follows, by considering the mechanical speed as a constant parameter, (Maes and Melkebeek, 2000; Wolbank *et al.*, 2002):

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

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. 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:

$$\frac{d}{dt}e = (A + GC)e + \Delta A\hat{x} \qquad (10)$$

$$\Delta A = A - \hat{A}\begin{bmatrix} 0 & 0 & 0 & pK\Delta\omega_r \\ 0 & 0 & -pK\Delta\omega_r & 0 \\ 0 & 0 & 0 & -p\Delta\omega_r \\ 0 & 0 & p\Delta\omega_r & 0 \end{bmatrix} \qquad (11)$$

we consider the following Lyapunov function,

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

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

$$\begin{aligned}\frac{d}{dt}V = e^T\left\{(A(w_r)+GC)^T + (A(w_r)+GC)\right\}e \\ -2K\Delta k_r(e_1\hat{x}_4 - e_2\hat{x}_3) + \frac{2}{\lambda}\Delta w_r \dot{\hat{w}}_r\end{aligned} \tag{13}$$

From Eq. 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:

$$\hat{\omega}_r = \lambda K(e_1\hat{x}_4 - e_2\hat{x}_3) \tag{14}$$

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:

$$\hat{\omega}_r = k_p(e_1\hat{x}_4 - e_2\hat{x}_3) + k_i\int_0^t (e_1\hat{x}_4 - e_2\hat{x}_3)dt \tag{15}$$

where and are positive gains

REGULATOR DESIGN

The transfer of the manipulated variable is affected by one or more nonlinear elements (hysteresis, saturation). 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.

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, (Cao *et al.*, 2002; Zaccarian and Teel, 2004).

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 two techniques are analyzed starting from the simulation of the transients according to:

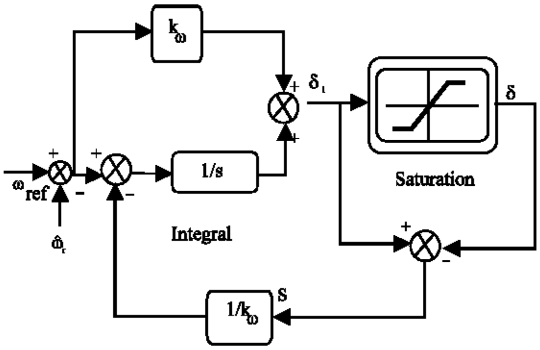

Fig. 4: Structure of the anti-windup PI system

Comparison on the level of the regulation speed: Figure 5 and 6, show the settling performance comparison between two techniques. The DTC presents a high dynamics at starting instant and rapid load torque disturbance rejection without overshoot compared to the IFOC. The same remarks can be observed for the responses of the stator flux magnitude show in Fig. 7 and 8 or one sees an almost instantaneous establishment for the DTC compared to the IFOC what improves moreover dynamics of the machine. The DTC presents a more oscillating current at starting. Indeed contrary to the IFOC with uses a regulation loop of the current. The DTC does not contain a current regulator loops, illustrate in Fig. 7, 8.

Inversion of the speed: The estimated speed, torque and the stator current waveform obtained with IFOC and DTC schemes are shown in Fig. 9, 10, respectively. We applied a changing of the speed reference from 100 rad/sec to -100 rad/sec at t = 0.3s. 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.

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 s and t=0.7s after a leadless

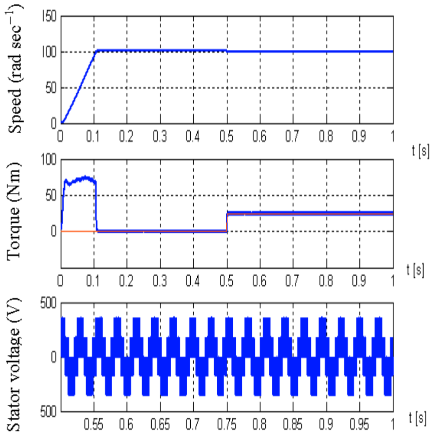

Fig.5: Estimated speed, torque and stator voltage responses of DTC scheme

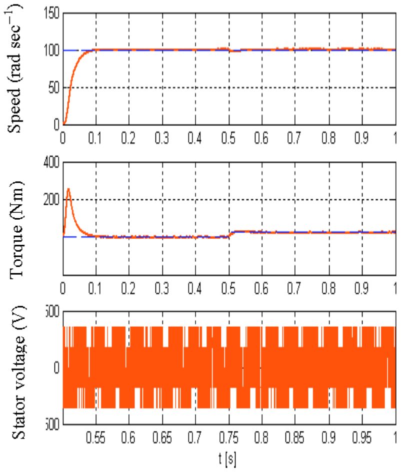

Fig. 6: Estimated speed, torque and stator voltage responses of IFOC scheme

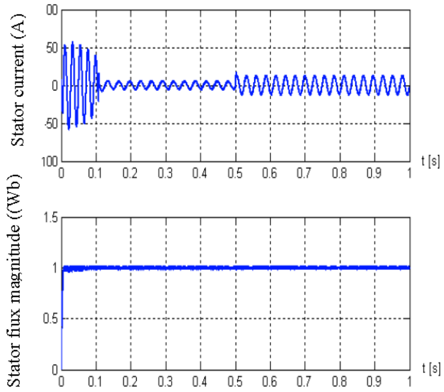

Fig. 7: Stator flux magnitude and stator current responses of DTC scheme

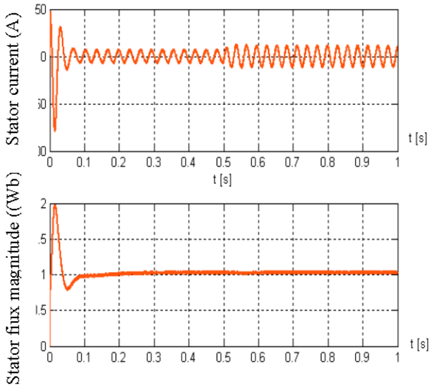

Fig. 8: Stator flux magnitude and stator current responses of IFOC scheme

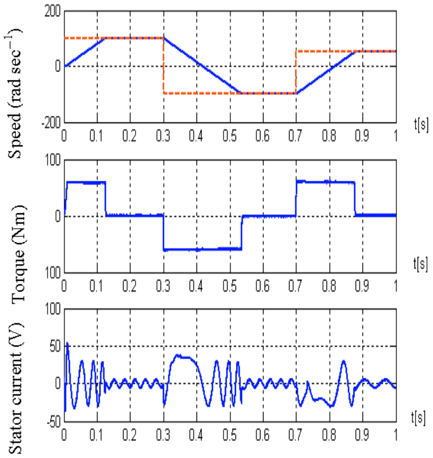

Fig. 9: Four quadrant speed estimation and torque and stator current responses of DTC scheme

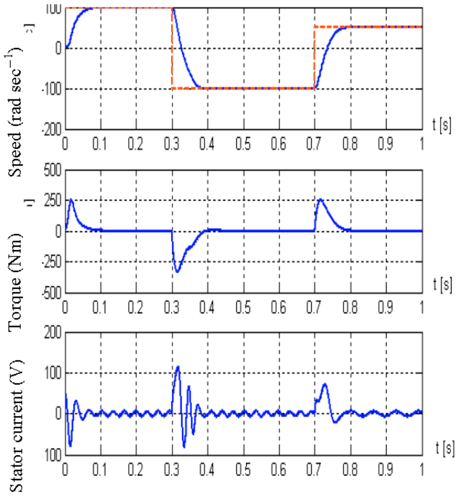

Fig. 10: Four quadrant speed estimation and torque and stator current responses of IFOC scheme

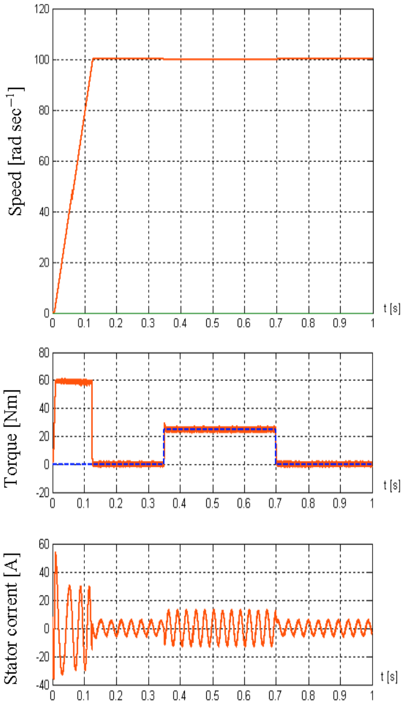

Fig. 11: Estimated speed (load torque applied between 0.35s-0.7s) response of DTC scheme

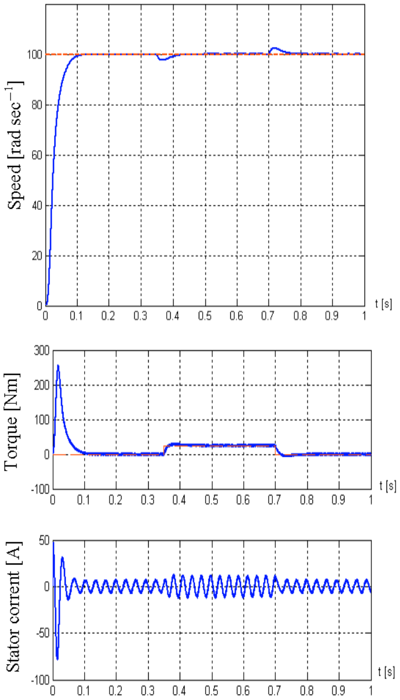

Fig. 12: Estimated speed (load torque applied between 0.35s-0.7s) response IFOC scheme

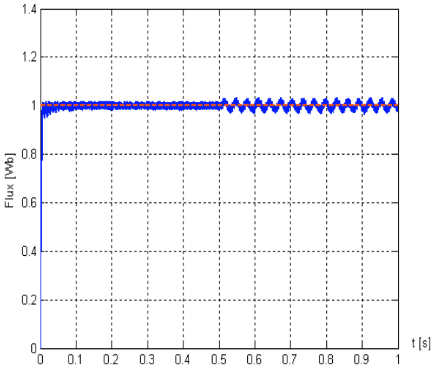

Fig. 13a: Evolution of a real stator flux magnitude developed by the induction motor

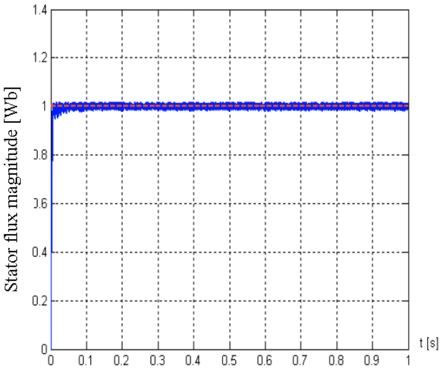

Fig. 13b: Evolution of an estimated stator flux magnitude developed by the adaptive observer

starting. Figure 11, 12 illustrate the torque responses, estimated speed and the stator current. We can see that the insensibility of the control algorithm to load torques variations in the case of DTC compared to the IFOC.

Effect of the stator resistance variation: To highlight the effect of the stator resistance variation in the case of DTC, one carried out to vary stator resistance. The Fig. 13-a, 13-b illustrate the evolution of the stator flux magnitude with an increase of 100 % of the stator resistance at t=0.5s. We note that according to this result that the observer corrects well the stator flux magnitude and follows its reference in established mode.

CONCLUSION

The aim of this study 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. In 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 note 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.

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