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Dspace Based Experimental Results of Direct Torque Control (DTC) of Induction Machine with Speed Control Using IP Controller

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Abstract: This study presents simulation and experimental results of DTC of induction machine, using an IP controller to improve induction machine speed control. The experimental results were obtained by practical implementation on a dSPACE 1104 board for a 1.5 kW induction machine. The aim of this reserach is to give an experimental performance analysis of DTC and IP speed controller in term of torque, currents distortions and stator flux, to validate simulation. Simulation and experimental results have been made to illustrate the performances of the presented control strategy.

Key words: DTC, dSPACE 1104, IP controller, speed control, stator flux, induction machine

INTRODUCTION

Traditionally, variable speed electric machines were based on DC motors, since, the magnetic flux and torque are easily controlled by the stator and rotor current, respectively (Ramya *et al*., 2012). For the last two decades, DC motors was replaced by AC motors. Induction Machine (IM) is one of the robust AC motors that have been widely used in industry. However, due to their highly coupled non-linear structure, a high performance control of IM is a challenging problem (Chaikhy *et al*., 2011a, b). During the last decade, a new control method called DTC has been created. DTC has received enormous attention in industrial motor drive applications. The main reason for its popularity is due to its simple structure, robustness against rotor parameter variations and quick dynamic response (Jidin *et al*., 2012).

Moreover, the design of the speed controller greatly affects the performance of the drive. Concerning The IP controllers which are widely used in industrial control system applications, they have a simple structure and can offer a satisfactory performances.

To validate our approach, the IP controller performances, for IM speed drive based on Direct Torque Control (DTC) strategy were investunder MATLAB/Simulink and then practically using a dSPACE 1104 board. In order to show the performances of the proposed IP controller. Both simulation and practical tests show that the IP in speed tracking and disturbances rejection.

MATERIALS AND METHODS

Principe of DTC: Since, M. Depenbrock and I. Takahashi proposed DTC for IM in the middle of 1980's, more than decade has passed. It is getting more and more popular now a days (Chaikhy *et al*., 2011a, b). The instantaneous values of the stator flux and torque are calculated from stator variable by using a closed loop estimator (Takahashi and Noguchi, 1986) as shown in Fig. 1, stator flux and torque can be controlled directly and independently by properly selecting the inverter switching configuration.

By using a (α, β)-stationary stator reference frame, the stator flux linkages φ and electromagnetic torque are calculating by using:

$$\varphi_s = \sqrt{\varphi_{s\alpha}^2 + \varphi_{s\beta}^2} \quad (1)$$

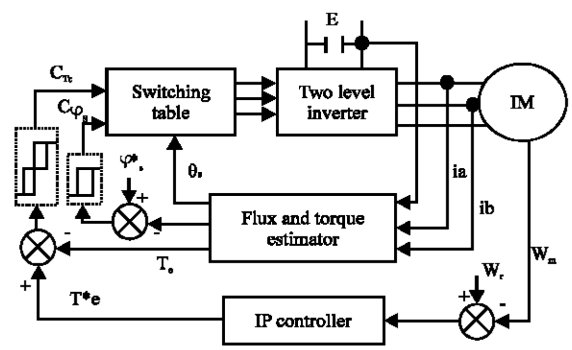

Fig. 1: Block diagram of the DTC control technique

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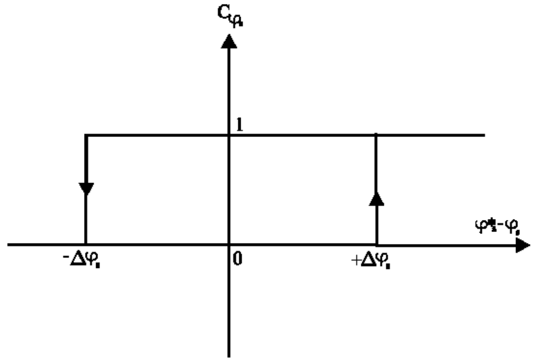

Fig. 2: Flux hystersis comparator

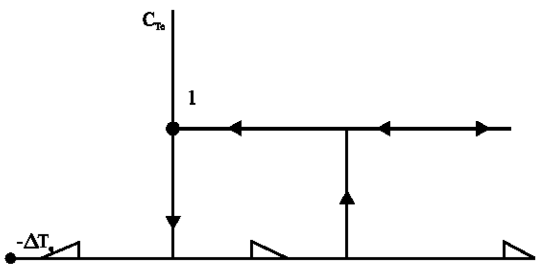

Fig. 3: Torque hysteresis comparator

Where:

$$\varphi_{s\alpha} = \int_0^t \left(V_{s\alpha} - R_s I_{s\alpha} \right) dt \quad (2)$$

$$\varphi_{s\beta} = \int_0^t \left(V_{s\beta} - R_s I_{s\beta} \right) dt \quad (3)$$

The angle θ_s is equal to:

$$\theta_s = \tan^{-1}\left(\frac{\varphi_{s\beta}}{\varphi_{s\alpha}} \right) \quad (4)$$

$$T_e = p\left| \varphi_{s\alpha} I_{s\beta} - \varphi_{s\beta} I_{s\alpha} \right| \quad (5)$$

The error between the estimated torque T_e and the reference torque T_e^* is the input of a three level hysteresis comparator whereas the error between the estimated stator flux magnitude φ_s and his reference stator flux magnitude φ_s^* is the input of a two level hysteresis comparator.

Figure 2 and 3 illustrate the torque and flux comparators, respectively. The selection of the appropriate voltage vector is based on the switching table given in Table 1. The input quantities are the flux sector and he outputs of the two hysteresis comparators (Fig. 4).

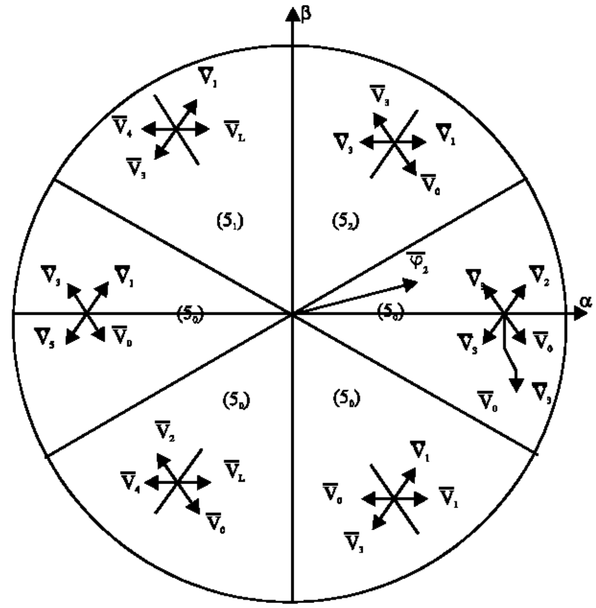

Fig. 4: Influence of the voltage vector selected on the variation of stator flux modulus and torque

Table 1: Switching table

	Comparator	Levels					
	Flux: $C_{\varphi s}$	1			-1		
Sectors	Torque: C_{Te}	1	0	-1	1	0	-1
1	(330°, 30°)	V_2	V_0	V_6	V_3	V_7	V_5
2	(30°, 90°)	V_3	V_7	V_1	V_4	V_0	V_6
3	(90°, 150°)	V_4	V_0	V_2	V_5	V_7	V_1
4	(150°, 210°)	V_5	V_7	V_3	V_6	V_0	V_2
5	(210°, 270°)	V_6	V_0	V_4	V_1	V_7	V_3
6	(270°, 330°)	V_1	V_7	V_5	V_2	V_0	V_4

V_0 = (0, 0, 0); V_1 = (1, 1, 0); V_3 = (0, 1, 0); V_4 = (0, 1, 1); V_5 = (0, 0, 1); V_6 = (1, 0, 1); V_7 = (1, 1, 1)

To determine stator vector voltage to be applied, first the circular trajectory of the stator flux is divided into six symmetrical sectors referred as the inverter voltage vectors (Ouboubker *et al.*, 2014). Then, the effect of each stator voltage on the flux and torque is studied.

IP speed controller synthesis: The Integral Proportional (IP) controller is mainly different from PI controller by the fact that it does not present any zero in the closed loop transfer function (Jarray, 2000). Therefore, the delivered reference torque will not present discontinuities when a speed step or a load torque perturbation is applied (Jebali *et al.*, 2004). The rotor speed closed loop with the IP controller is presented by the block diagram in Fig. 5. With:

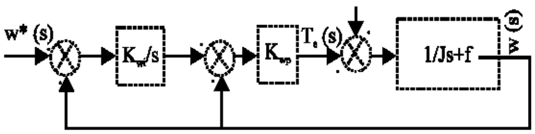

Fig. 5: Closed loop speed controller

$$F(s)=\frac{1}{Js+f} \tag{7}$$

In case of no disturbances (T_r = 0), the transfer function representing the dynamics of the system is given by:

$$\frac{w(s)}{w^*(s)}=\frac{1}{\frac{\tau_1}{g_1K_{wi}}sh+\frac{1}{g_1K_{wi}}s+1} \tag{8}$$

Where:

$$\tau_1=\frac{J}{K_{wp}+f} \tag{9}$$

And:

$$g_1=\frac{K_{wp}}{K_{wp}+f} \tag{10}$$

For a step speed consign, the Eq. 11 should be respected in order to have an aperiodic response of the above presented system:

$$K_{wi}=\frac{1}{4g_1\tau_1} \tag{11}$$

In this case, the time-constant τ_2 of the closed loop system and the proportional gain become:

$$\tau_2=2\tau_1 \tag{12}$$

$$K_{wp}=\frac{J-\tau_1 f}{\tau_1} \tag{13}$$

For a response time t_{pw} = 0.4 sec at 5% of the speed which corresponds to a time-constant equal to 0.08 sec, we found K_p = 0.54 and K_i = 5.94.

RESULTS AND DISCUSSION

Simulation results: In order to valid the quality of the drives, a simulation test on 1.5 kW induction machine has been performed. Induction Motor data used are shown in Table 2.

Table 2: Induction machine parameters

Variables	Values
Rate Power (P)	1.5 kW
Voltage (V)	220/380 V
Number of pair poles (n_p)	2
Stator resistance (R_s)	5.63 Ω
Rotor resistance (R_r)	2.62 Ω
Stator self-inductance (L_s)	0.018 H
Rotor self-inductance (L_r)	0.018 H
Mutual inductance (M)	0.20 H
Tatol inertia (J)	0.023 kg m^2
Friction coefficient (f)	0.00155 Nm sec

The simulation results corresponding to the rotor speed, the electromagnetic torque, the stator flux and the stator currents. We use: DC voltage E = 600 V, stator flux reference φ_{sref} = 1 Wb, $\Delta\varphi_s$ = Wb 0.01, ΔT_e = 0.02 Nm, the sampling time T_{ech} = 1e^{-5}sec.

The first test aims to evaluate the speed tracking efficiency. In fact as shown in Fig. 6, starting from a steady state of 500, 500 rpm acceleration and deceleration steps were applied, respectively at t = 1.5 sec and t = 4.5 sec. We remark that the IP speed controller has achieved the test goals: no over/ under-shoots and better constancyin steady state. Figure 7-9 presents, respectively torque response, stator flux response and stator currents responses. The stator flux Fig. 8 tracks its reference with good performance. The stator currents, Fig. 9 are sinusoidal and present less harmonics.

The second test is to evaluate the disturbances rejection effectiveness. In fact, during this test, the speed was maintained at 600 rpm and a disturbance (75% of load torque) was inserted at t = 1.5 sec and removed at t = 3 sec as seen in Fig. 10 shows that the proposed IP controller offers significant improvements; the load disturbance rejection has been done rapidly with the proposed controller. Moreover, the developed torque can follow the load torque. The compensations for disturbance are achieved by developed electromagnetic torque automatically.

Experimental setup and practical results: The realized experimental setup is shown in Fig. 11. It consists of an IGBTs voltage inverter, the 1.5 kW induction motor (coupled in star) is driven under load with the help of DC generator mechanically coupled to the motor and having the following characteristics: 1 kW, 220 V, 6.5 A, 2520 rpm. The latter supplies a 4 kW resistive bank to produce different load torques, dSPACE 1104 board based on a 250 MHz 603-PowerPC-64 bit processor and a slave-DSP based on a 20 MHz TMS320F240-16-bit microcontroller is used. The dSPACE works on MATLAB/Simulink R2013b platform. dSPACE board is used with control desk software which makes the record of the results easy. It helps also by making the development of controllers effective and automates the experiments. With the

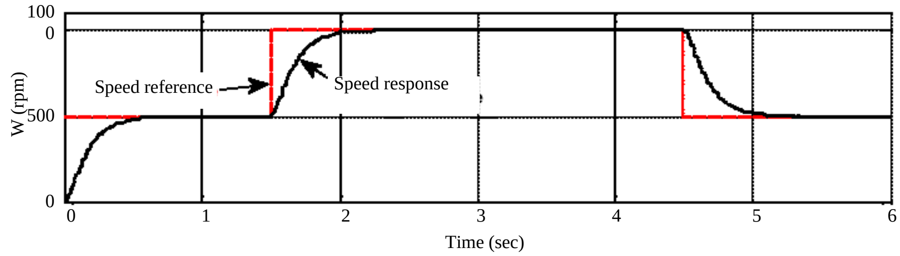

Fig. 6: Speed responses: 500 rpm acceleration/deceleration

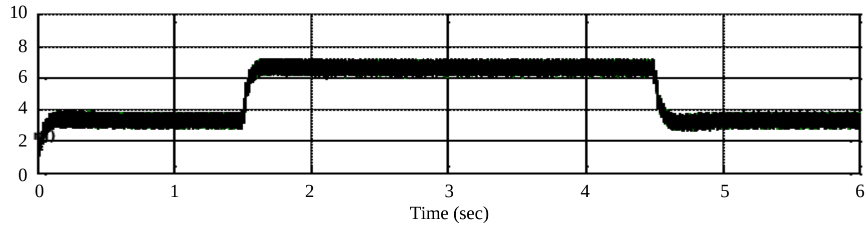

Fig. 7: Torque response

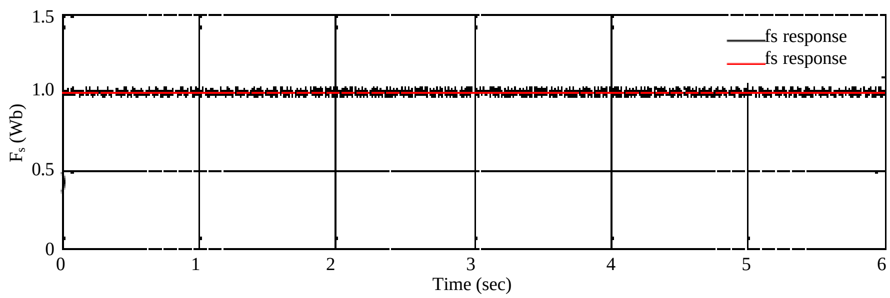

Fig. 8: Stator flux response

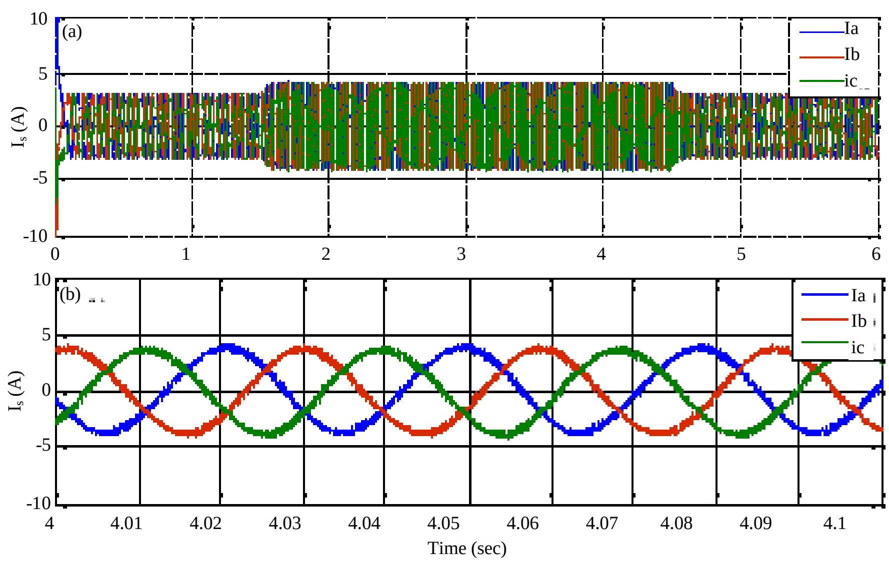

Fig. 9: Stator currents responses: a) Stator currents and b) Zoom on stator currents

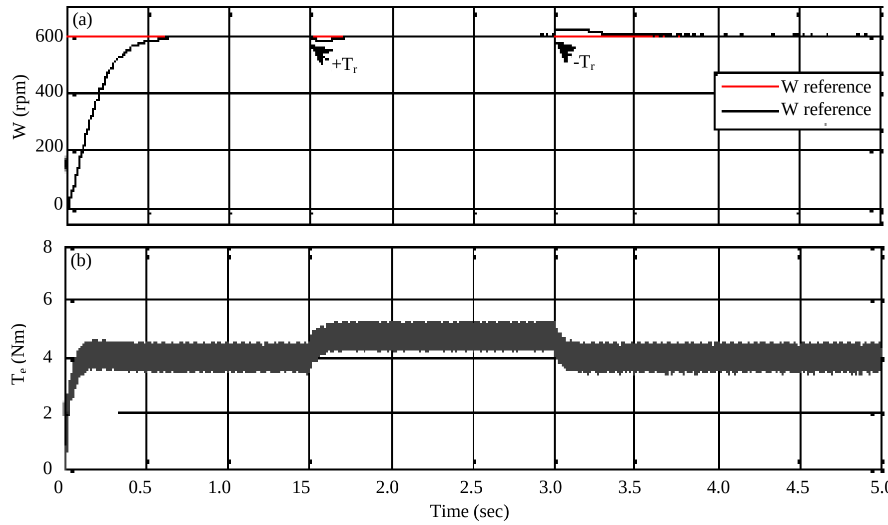

Fig. 10: Disturbances rejection response for 75% of load torque and 600 rpm speed reference with IP controller; a) Speed response and b) Torque response

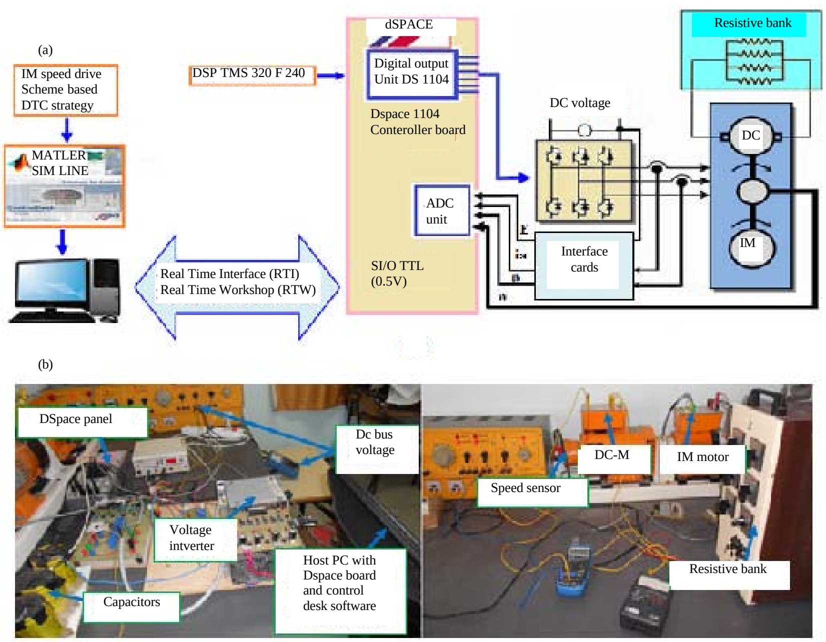

Fig. 11: a) Experimental platform and b) Photograph of experimental setup

dSPACE 1104 the user can design the drive in MATLAB/SimulinkR2013b and with the help of Real-Time Workshop (RTW) of MATLAB/Simulink R2013b and Real Time Interface (RTI), the user can convert them to real-time codes, a tachymeter is used for speed sensor (15 V for 1500 rpm).

Practical results: To validate the simulation results, different practical tests were carried out under the following conditions: DC voltage E = 150 V, Stator flux reference φ_{sref} = 35.0 Wb, $\Delta\varphi_s$ = 01.0 Wb, Δt_e = 0.02 Nm the sampling time T_{ech} = 1e^{-4}sec. The practical results corresponding to the rotor speed, the electromagnetic torque, the stator flux and the stator currents. The first test aims to evaluate the speed tracking efficiency. In fact as shown in Fig. 12, starting from a steady state of 500, 500 rpm acceleration and deceleration steps were applied, respectively at t = 8.4 and t = 18.4 sec.

Figure 12 shows that IP speed responses present a symmetric (acceleration/deceleration) speed responses, no over/under-shoots and better constancy in steady state. The experimental stator currents response Fig. 14 is sinusoidal and present less harmonics. The stator flux Fig. 15 tracks its reference (0.35 Wb) with good performance.

The second test is to evaluate the disturbances rejection effectiveness. In fact, during this test, the speed was maintained at 600 rpm and a disturbance (75% of load torque) was inserted at t = 3.85 sec and removed at t = 12.1 sec as seen in Fig. 16 shows that the proposed IP controller offers significant improvements; the load disturbance rejection has been done rapidly with the proposed controller. Moreover, the developed torque can follow the load torque. The compensations for disturbance are achieved by developed electromagnetic torque automatically.

It can be seen from this practice test that the actual speed of the proposed IP controller regained the imposed reference value after the loading and unloading of the motor.

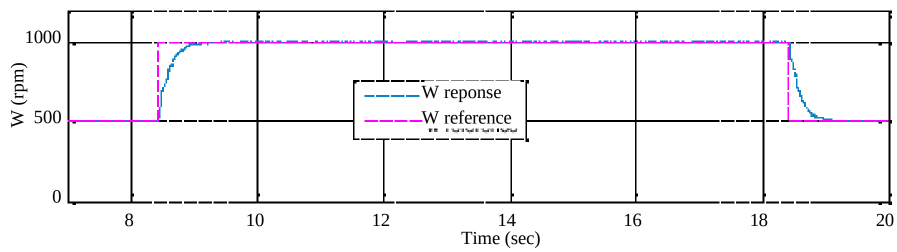

Fig. 12: Experimental speed responses: 500 rpm acceleration/deceleration

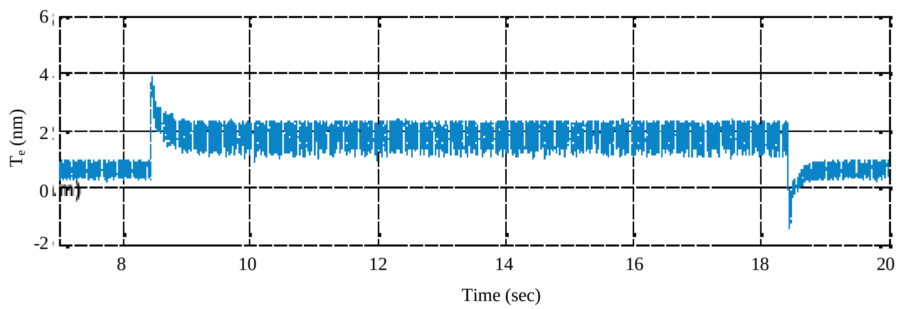

Fig. 13: Experimental torque response

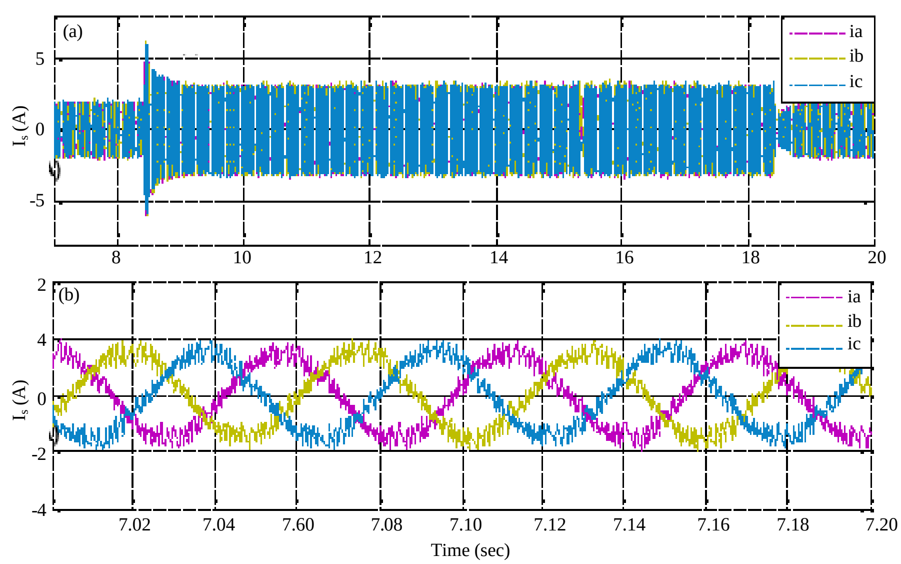

Fig. 14: Experimental stator currents responses; a) Stator currents and b) Zoom on stator currents

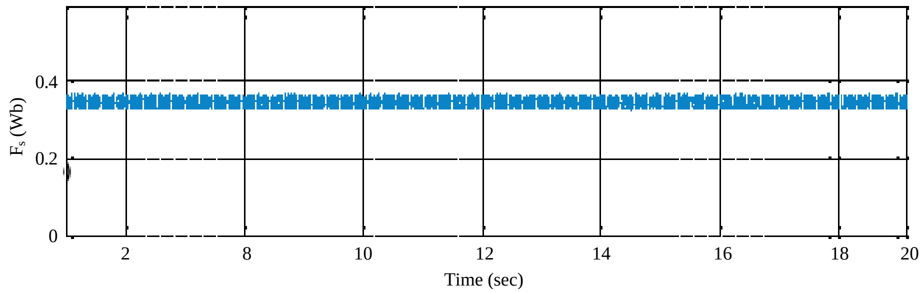

Fig. 15: Experimental stator flux response

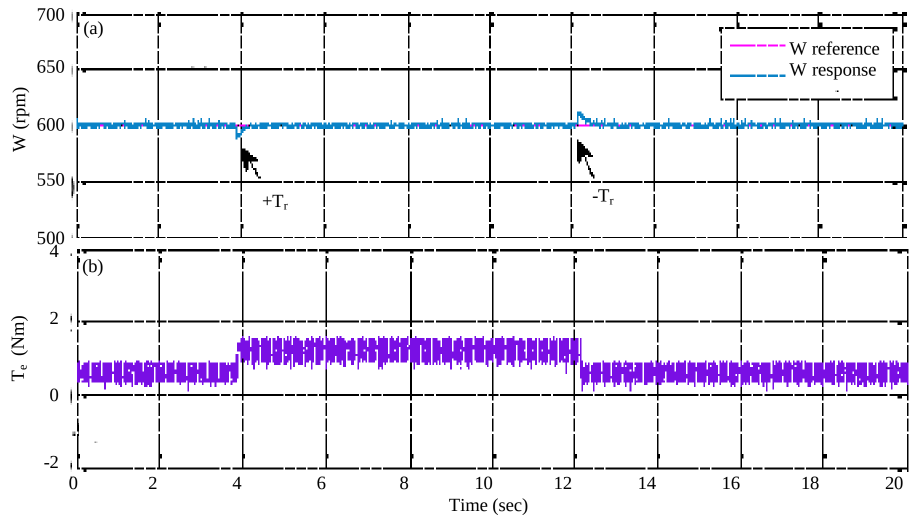

Fig. 16: Experimental disturbances rejection response for 75% of load torque and 600 rpm reference speed with IPcontroller; a) Speed response and b) Torque response

CONCLUSION

In this study, we have presented the simulation and experimental results of DTC of induction machine combined with an IP speed controller. The Direct Torque Control (DTC) is an important alternative method for the induction motor drive with its high performance and simplicity. The experimental results show that the DTC method applied to an induction motor using an IP controller of speed present most interest and contribute to improvement of system response performances.

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