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A modified load angle based DTC-SVM scheme for three-phase induction motors

Abstract. *This work proposes a direct torque control with space vector modulation based on load angle using PI controllers. This controller calculates dynamically the load angle between stator and rotor flux vectors using a PI controller. A reference of stator flux on stationary reference frame is calculated by using the load angle, rotor position and the stator flux magnitude. Another PI controller calculates the stator voltage to be supplied to the induction motor based on stator flux error. Thus, the electromagnetic torque necessary to supply the motor load is achieved. This strategy is easy to implement and experimental results are presented to validate the proposed strategy.*

Streszczenie. *W artykule opisano bezpośrednie sterowanie momentem z przestrzenną modulacja wektora bazującą na kącie obciążenia i regulatorze PI. Sterownik dynamicznie oblicza kąt między wektorami strumienia stojana i wirnika. Ta strategia jest łatwa do zastosowania co potwierdziły wyniki eksperymentu. (**Bezpośrednie sterowanie momentem trójfazowego silnika indukcyjnego bazujące na obliczaniu kąta obciążenia**)*

Keywords: Direct Torque Control, PI Controllers, Load Angle, Induction Motor.
Słowa kluczowe: bezpośrednie sterowani momentem DTC, silnik indukcyjny.

Introduction

The three-phase induction motors (IM) are widely used in industrial applications today due to its low cost, simple construction, reliability and robustness. In the last years direct torque control (DTC) strategy has become a popular technique for three-phase IM drives as it provides a fast dynamic torque response and robustness under machine parameter variations without the use of current regulators.

The induction machine high dynamic performance can be achieved by using a DTC strategy. These strategies can based on, e.g., voltage-vector selection using switching table [1], direct self-control [2]. An alternative approach to reduce the torque ripples is based on space vector modulation (SVM) technique [3], [4].

An alternative solutions for variable switching frequency problem, DTC strategies operating at constant switching frequency are proposed by using PI [5], deadbeat [6], slide mode [7] and predictive [8, 9], Fuzzy [10, 11] controllers. The controllers calculate the required stator voltage vector, averaged over a sampling period. These strategies have satisfactory flux and torque response although they do not present low speed operation results.

A DTC strategy that has simple one step stator flux control algorithm which avoids coordinate rotation and predictive controllers is presented in [13]. However, this scheme has a steady state error in the flux response. An interesting strategy based on load angle estimation is presented in [12].

To overcome the steady state error in the flux response in [13], this paper proposes a DTC strategy that allows a null steady state error in flux response using PI controllers. This controller calculates dynamically the load angle between stator and rotor flux vectors using a PI controller. A reference of stator flux on stationary reference frame is calculated by using the calculated load angle, rotor position and the stator flux magnitude. Another PI controller calculates the stator voltage to be supplied to the induction motor based on stator flux error. Thus, the electromagnetic torque necessary to supply the motor load is achieved. This strategy is easy to implement and experimental results are presented to validate the strategy operation.

Dynamical Equations of the Three-Phase Induction Motor

By utilizing the definitions of the fluxes, currents and voltages space vectors, the dynamical equations of the three-phase IM in stationary reference frame can be put into the following mathematical form [14]:

$$\vec{u}_s = R_s\vec{i}_s + \frac{d\vec{\psi}_s}{dt} \tag{1}$$

$$0 = R_r\vec{i}_r + \frac{d\vec{\psi}_r}{dt} - j\omega_r\vec{\psi}_r \tag{2}$$

$$\vec{\psi}_s = L_s\vec{i}_s + L_m\vec{i}_r \tag{3}$$

$$\vec{\psi}_r = L_r\vec{i}_r + L_m\vec{i}_s \tag{4}$$

Where $\vec{u}_s$ is the stator voltage space vector, $\vec{i}_s$ and $\vec{i}_r$ are the stator and rotor current space vectors, respectively, $\vec{\psi}_s$ and $\vec{\psi}_r$ are the stator and rotor flux space vectors, ω_r is the rotor angular speed, R_s and R_r are the stator and rotor resistances, L_s, L_r and L_m are the stator, rotor and mutual inductance, respectively.

The electromagnetic torque is expressed in terms of the cross product of the stator and the rotor flux space vectors.

$$t_{em} = \frac{3}{2}P\frac{L_m}{L_rL_s\sigma}\vec{\psi}_r \times \vec{\psi}_s \tag{5}$$

$$t_{em} = \frac{3}{2}P\frac{L_m}{L_rL_s\sigma}\left|\vec{\psi}_r\right|\left|\vec{\psi}_s\right|\sin(\gamma) \tag{6}$$

Where γ is the load angle between stator and rotor flux space vectors, P is a number of pole pairs and $\sigma = 1 - L_m^2/(L_sL_r)$ is the dispersion factor.

Three-phase Induction Motor Direct Torque Control

If the sample time is short enough, such that the stator voltage space vector is imposed to the motor keeping the stator flux constant at the reference value. The rotor flux will become constant because it changes slower than the stator flux. The electromagnetic torque (6) can be quickly changed by changing the angle γ in the desired direction. This angle γ can be easily changed when choosing the appropriate stator voltage space vector.

For simplicity, let us assume that the stator phase ohmic drop could be neglected in (1). Therefore $d\vec{\psi}_s/dt = \vec{u}_s$. During a short time Δt, when the voltage space vector is applied it has:

$$\Delta\vec{\psi}_s \approx \vec{u}_s \cdot \Delta t \tag{7}$$

Thus the stator flux space vector moves by $\Delta\vec{\psi}_s$ in the direction of the stator voltage space vector at a speed which is

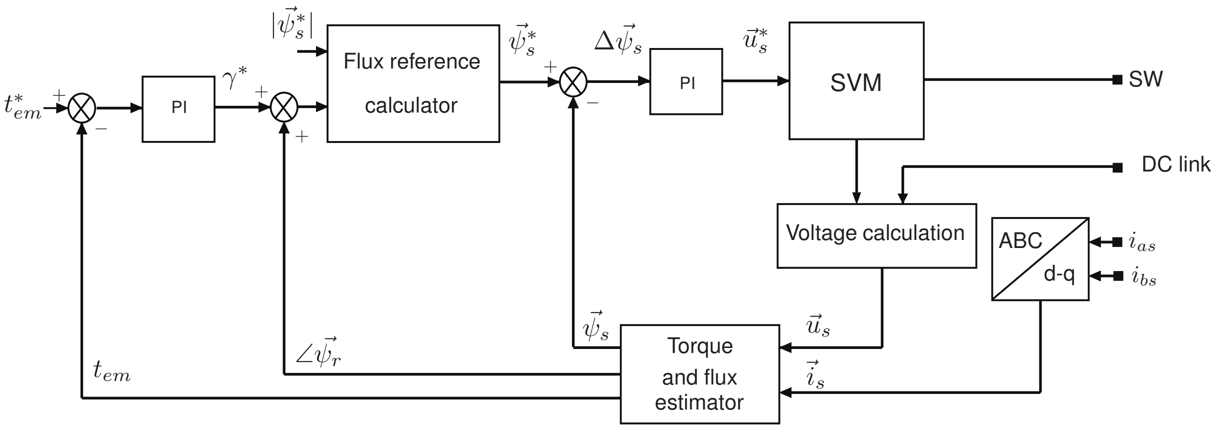

Fig. 1. Direct torque control with space vector modulation and PI controllers.

proportional to the magnitude of the stator voltage space vector. By selecting step-by-step the appropriate stator voltage vector, it is possible to change the stator flux in the required direction.

Direct Torque Control Based on Load Angle and PI controllers

In Fig. 1, we show the block diagram of the proposed DTC-SVM scheme with PI controller. This scheme is an alternative to the classical DTC schemes [1], [2] and [3]. In this scheme, the load angle γ^* is not prefixed but it is calculated by a PI controller. Equation (6) shows that the angle γ^* determines the electromagnetic torque which is necessary to supply the load. The PI controller determines this angle from the torque error. Details about this controller is going to be presented in the next section.

In Fig. 2, we can see the scheme of the power electronics drive used in our simulation. The control signals for three-phase, two-level inverter is generated by the DTC-SVM block shown in Fig. 1.

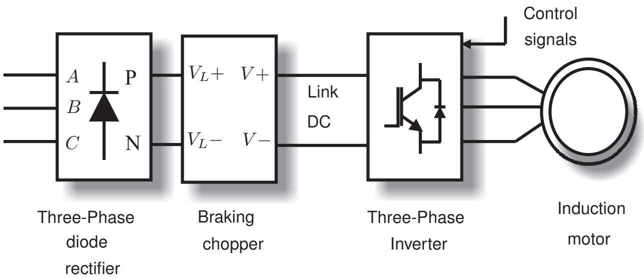

Fig. 2. Scheme of power electronics drive.

Stator Flux Reference Calculation

As shown in Fig. 3, in stationary reference frame, the stator flux reference $\vec{\psi}_s^*$ can be decomposed in two perpendicular components ψ_{ds}^* and ψ_{qs}^*. The addition of the angle determinate γ^*, which is the output of the PI controller, to the estimated rotor flux angle $\angle\vec{\psi}_r$ permits to estimate the next angle of the stator flux reference.

In this paper, the magnitude of stator flux reference is considered constant. We use the relation, presented in (8), to calculate the stator flux reference vector.

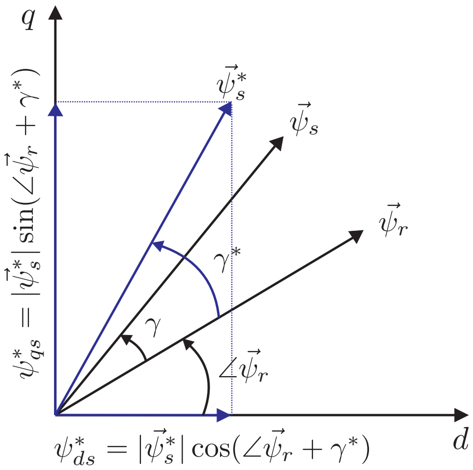

Fig. 3. Load angle γ^* between stator flux reference $\vec{\psi}_s^*$ and rotor flux $\vec{\psi}_r$ in stationary reference frame.

$$\vec{\psi}_s^* = |\vec{\psi}_s^*|\cos(\gamma^* + \angle\vec{\psi}_r) + j|\vec{\psi}_s^*|\sin(\gamma^* + \angle\vec{\psi}_r) \tag{8}$$

With the application of the stator voltage $\vec{u}_s$ during a short time Δt it is possible to reproduce a flux variation $\Delta\vec{\psi}_s$. Notice that the stator flux variation is nearly proportional to the stator voltage space vector as seen in the equation (7).

Stator Voltage Calculation

The inputs for the stator voltage calculator block in Fig. 1 are the DC link voltage $\mathbf{U_{dc}}$ and the inverter switch state (S_a, S_b, S_c).

The stator voltage vector $\vec{u}_s$ is determined as:

$$\vec{u}_s = \frac{2}{3}\left[(S_a - \frac{S_b + S_c}{2}) + j\frac{\sqrt{3}}{2}(S_b - S_c)\right]U_{dc} \tag{9}$$

Electromagnetic Torque and Flux Estimation

The stator flux space vector estimation depends of the back electromotive force (emf), it is:

$$\vec{\psi}_s = \int (\vec{u}_s - R_s \cdot \vec{i}_s) dt$$

$$\vec{\psi}_s = \int (\vec{\text{emf}}) dt \quad (10)$$

when the stator flux is calculate with equation (10) it has problems associated with a pure integrator. With the aim to solve this problem is used the integrator with an adaptive compensation method proposed in [15]. This method can be used to accurately estimate the motor flux including its magnitude and phase angle over a wide speed range.

Fig. 4 shows a block diagram of this method. The main idea of this method is the fact that the motor stator flux space vector is orthogonal to its back emf. The quadrature detector detect if the orthogonality between the estimated stator flux space vector and emf is maintained.

The operating principle of this method is explained by using a vector diagram shown in Fig. 5. The estimated stator flux space vector is a sum of two vectors, a feedforward vector $\vec{\psi}_1$ which is the output of the Low Pass (LP) filters (ψ_{d1} and ψ_{q1}) and a feedback vector $\vec{\psi}_2$ which is composed of ψ_{d2} and ψ_{q2}. Ideally, the stator flux space vector $\vec{\psi}_s$ should be orthogonal to the $\vec{\text{emf}}$, and the output of the quadrature detector is zero. When an initial value or dc drift is introduced to the integrator, the above orthogonal relation is lost, and the phase angle between the flux and emf vectors is no longer 90°, which yields an error signal defined by

$$\Delta\vec{e} = \vec{\psi}_s \cdot \vec{\text{emf}} / \left|\vec{\psi}_s\right|$$

$$\Delta\vec{e} = (\psi_{qs} \cdot \text{emf}_q + \psi_{ds} \cdot \text{emf}_d) / \left|\vec{\psi}_s\right|$$

$$\Delta\vec{e} = |\text{emf}| \cos(\gamma) \quad (11)$$

Assuming that the magnitude of the feedback vector $\vec{\psi}_2$ is increased to $\vec{\psi}'_2$ as shown in Fig. 5 due to a dc offset or initial value problem, the phase angle γ will be greater that 90°. The quadrature detector will generate a negative error signal. The output of the PI regulator ψ_{cmp} is reduced and so is the feedback vector. As a result, the stator flux space vector $\vec{\psi}'_s$ moves toward the original position of 90° until the orthogonal relationship between $\vec{\psi}_s$ and $\vec{\text{emf}}$ is reestablished. If γ is less than 90° for some reason, an opposite process will occur, which brings γ back to 90°. Therefore, the modified integrator with the adaptive control can adjust the flux compensation level ψ_{cmp} automatically to an optimal value such that the initial value and dc drift problems are essentially eliminated.

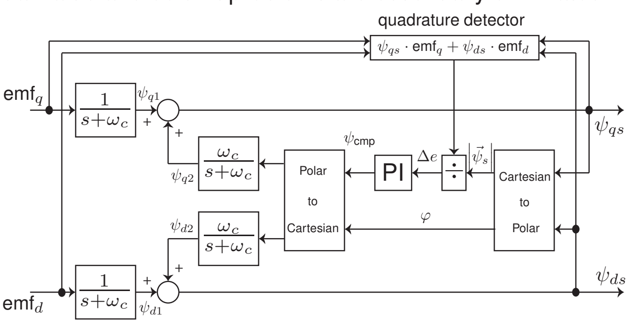

Fig. 4. Block diagram of the adaptive compensation method.

On the other hand, the rotor flux depends on the estimated stator flux and stator current space vectors. From the equations (3) and (4) we estimate the rotor flux space vector:

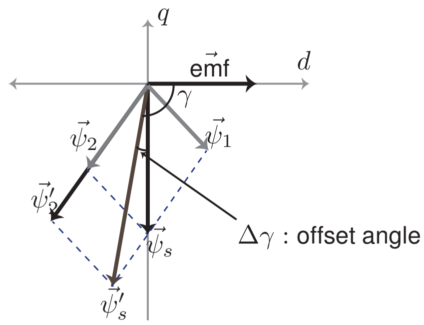

Fig. 5. Vector diagram showing the emf and flux linkage relationship.

$$\vec{\psi}_r = \frac{L_r}{L_m}\vec{\psi}_s - \frac{L_s L_r}{L_m}\sigma\vec{i}_s \quad (12)$$

With the components of $\vec{\psi}_r$ we can obtain the angle of the rotor flux:

$$\angle\vec{\psi}_r = \tan^{-1}\left(\frac{\psi_{qr}}{\psi_{dr}}\right) \quad (13)$$

With equations (10) and (12) in (5) it is possible to estimate the electromagnetic torque, it is:

$$t_{em} = \frac{3}{2} P \frac{L_m}{L_r L_s \sigma}(\psi_{dr}\psi_{qs} - \psi_{qr}\psi_{ds}) \quad (14)$$

Stator Voltage Reference Calculation

The proposed DTC strategy uses a PI controller to generate a stator flux vector reference based on calculated load angle (8). Thus, the PIs controllers will process the error between the calculated stator flux vector and its references and it will calculate the stator voltages references to be applied to the motor. This controller will allow that the torque and flux will reach the desired values with no steady state error. The expression that calculates the stator voltages references are done by:

$$u_{ds} = \left(K_p + \frac{K_i}{s}\right)(\psi^*_{ds} - \psi_{ds}) \quad (15)$$

$$u_{qs} = \left(K_{p1} + \frac{K_{i1}}{s}\right)(\psi^*_{qs} - \psi_{qs}) \quad (16)$$

Where $s \equiv d/dt$ and the stator flux references are calculated by using (8)

$$\psi^*_{ds} = |\vec{\psi}^*_s| \cos(\gamma^* + \angle\vec{\psi}_r) \quad (17)$$

and

$$\psi^*_{qs} = |\vec{\psi}^*_s| \sin(\gamma^* + \angle\vec{\psi}_r) \quad (18)$$

and K_p, K_i, K_{p1} and K_{i1} are the gains of the PIs controllers. Thus, if the gains was corrected adjusted the torque and flux loop will have null steady state error.

Experimental Results

The DTC strategy were implemented using a Texas Instruments DSP TMS320F28335 platform. The system consists of a three-phase voltage source inverter with insulated-gate bipolar transistors (IGBTs) and the three-phase induction motor shown in the appendix. The stator voltage commands are modulated by using symmetrical space vector PWM with switching frequency equal to 10 kHz. The DC link voltage of the inverter is 350 V and a conventional PI controller generates a torque reference by using the speed error. The flux and torque estimation, the DTC strategy and speed controller have the same sampling frequency of 10 kHz. The encoder resolution is 3600 pulses per revolution. The experimental setup is shown in Figure 6.

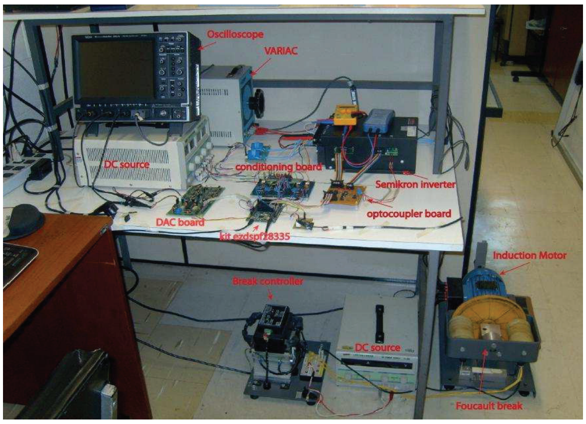

Fig. 6. Experimental setup.

Three tests are made and in all tests the reference of stator flux is $1pu$. In the first no-load test a step of speed reference from $0pu$ to $0.5pu$ is applied to the speed controller. The test is shown in Fig. 7. This result confirms the satisfactory performance of the DTC load angle controller due to the fact that the speed reaches the reference.

In the second no-load test, the speed reference is changed from $0.5pu$ to $-0.5pu$ and again to $0.5pu$ is applied to the speed controller and it is shown in Fig. 8. Again, the satisfactory performance of the DTC load angle controller can be seen due to the fact that the speed reaches the reference in several speed conditions.

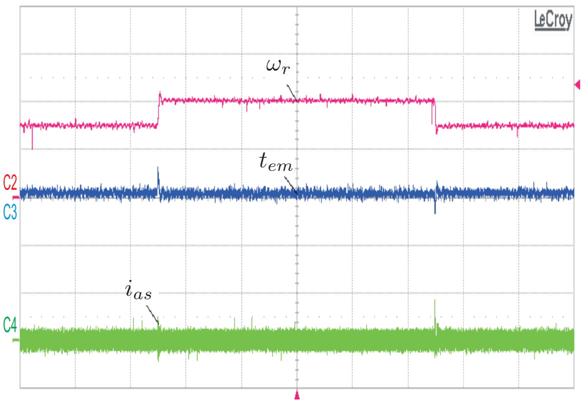

Fig. 7. Step of speed reference, torque and phase a current (C2: 0.2 pu/div; C3: 10 N.m/div; C4: 5 A/div; 5 s/div).

A full load test is the third. In this case, the speed reference is constant at $0.5pu$ and a $1pu$ of load toque is applied to the motor. The results are shown in Figures 9 and 10. Again, the satisfactory performance of the DTC load angle controller can be seen due to the fact that the speed reaches the reference in several conditions.

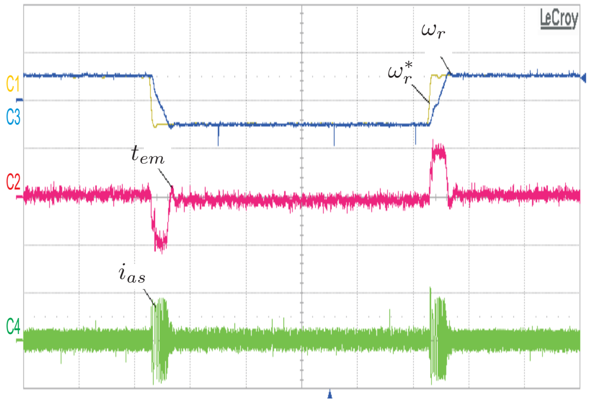

Fig. 8. Step of speed reference, torque and phase a current (C1,C3: 1 pu/div; C2: 10 N.m/div; C4: 5 A/div; 2 s/div).

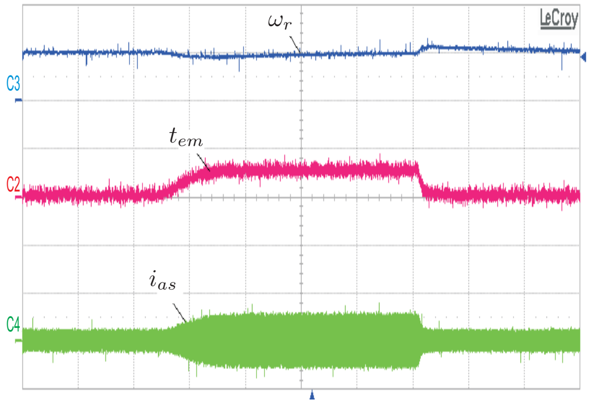

Fig. 9. Load test - speed reference, torque and phase a current (C2: 10 N.m/div; C3: 0.5 pu/div; C4: 5 A/div; 5 s/div).

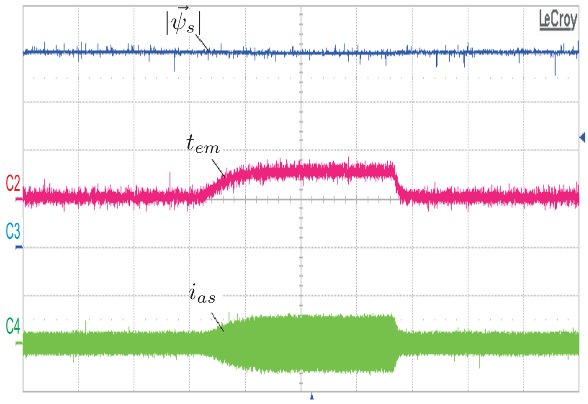

Fig. 10. load test - stator flux magnitude, torque and phase a current (C2: 10 N.m/div; C3: 0.2 Wb/div; C4: 5 A/div; 5 s/div).

The same full load test was made using the DTC strategy presented in [13]. The speed reference is constant at $0.5pu$ and a $1pu$ of load toque is applied to the motor. The result of the load test is presented in Fig. 11. It can be seen that the strategy has a flux error of 9% in steady state with and without load. So the motor will operate at weaking flux region. So, the machine can drive the full load but the losses will increase and efficient will decrease. Nowadays high efficient is very desirable and this type of operation at full load is not good. In this work the proposed DTC strategy allows a null error flux as can be seen comparing Figures 10 and 11.

Conclusion

In this paper a DTC strategy based on load angle has been proposed to be an alternative solution for correct the flux error in stead state operation as presented in DTC strat-

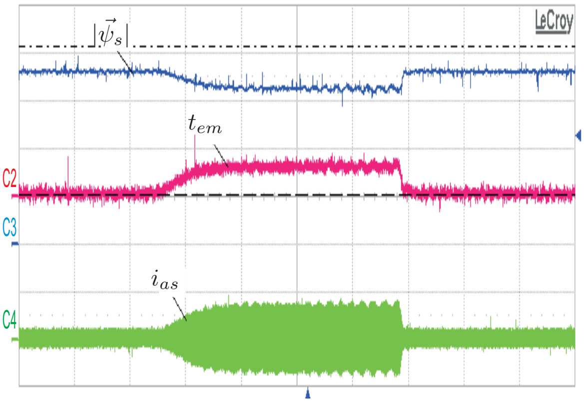

Fig. 11. Load test of DTC proposed by [13] (C2: 10 N.m/div; C3: 0.2 Wb/div; C4: 5 A/div; 5 s/div).

egy [13]. The strategy uses only PI controllers and mitigated the mentioned flux error. The strategy has simple implementation. The experimental results presented the satisfactory performance of the DTC controller due to the fact the torque, stator flux and speed reach the references. Although the gains of PI controllers have to be correctly design for the good performance of the controller. Hence, the proposed DTC strategy becomes an interesting tool for implementation IM drives.

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Appendix

The three-phase induction motor has the rated values $P_N = 1.1$ kW, $f_N = 60$ Hz, $U_N = 220$ V, $T_N = 6.1$ N.m, $\omega_N = 180.12$ rad/s, $P = 2$ pole pairs and the parameters $R_s = 5.56\Omega$, $R_r = 4.25\Omega$, $L_s = L_r = 0.309$ H, $L_m = 0.296$ H and $J = 0.0654\ K_g m^2$.

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