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Comparing the field oriented and direct torque vector controls applying on induction motors

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Abstract

Induction motors are widely used in the industry due to its relative low cost, low maintenance and high reliability. The development of the computer and electronic industry, as well as design of new control methods, has opened the door to control induction motors. In order to control the induction motors, scalar and vector control methods are used. Vector methods have faster response and more precision in controlling electric motors than scalar methods. The two main methods for vector control of induction motors are field oriented control and direct torque control. In this paper, the FOC and DTC vector control methods are fully described and MATLAB is used to evaluate and compare these two simulation methods in Simulink environment. The simulation results show that the DTC method has more flux and torque ripple than the FOC method but eliminates the complexity and limitations of the FOC method.

Keywords: *three phase induction motor, inverter, indirect vector control, direct torque control, lookup table*

1. INTRODUCTION

In most industrial sectors, electrical energy is one of the most important sources of energy. Since electric motors are the main consumers of energy in industry, the optimization of consumption in these motors is considered as a major alternative in terms of energy savings. One of the most effective ways to reduce the consumption of these motors is utilizing the motor drives or controllers. The main purpose of the induction motor control systems is to control the speed or torque. In this regard, in order to create the optimal dynamic response and to avoid entering the flux into the saturation zone, the flow should be controlled directly or indirectly. In general, control methods can be divided into two types of scalar and vector control. In vector control, in addition to the permanent response, the transient response quality is also considered. The above mentioned methods have different response speeds, but they are similar in terms of the amount of electrical energy savings in steady state. In applications where system performance in transient state is not significant, scalar methods are preferable because of their ease of construction and low cost. But if there is a need for fast and accurate response, vector control methods are used in spite of more and more computational capacity. Using the vector control, the performance of the AC machine looks like a DC machine. Vector control separates flux and torque, making it easier to control. One of the most important methods of vector control are field oriented control and direct torque control. In this paper, we have tried to make a complete assessment of the induction motor control using the FOC and DTC methods and have been expressed the advantages and disadvantages of each one. In Section 2, the FOC control principles are stated. Section 3 describes the principles of direct control of torque control. In Section 4, the FOC and DTC methods are simulated in MATLAB/Simulink, and the results have been compared. The paper Conclusion has been presented in Section 5.

2. FIELD ORIENTED VECTOR CONTROL

The basis of the performance of the FOC control method is that the component of the motor current responsible for the flux production and the torque component of the current is magnetically separated and therefore, as in the DC motor, controlling each of the flux and torque is possible independently. The purpose of the FOC control is to control the flux and torque of the machine, and to force the machine to follow the reference values regardless of load, machine parameters, and any external changes. In this paper, for analyzing the FOC control of the three-phase induction motor, the mathematical model of the motor in the rotating reference frame has been used.

2.1. Park transformation

Differential equations governing the motor's mathematical model, have time-variant coefficients due to the dependence of the parameters on the rotor position and the coupling between the rotor and stator phases. To solve this problem and to remove the time-variant parameters, the theory of the dqo axes has been used. The park equation is expressed in (1).

$$\begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (1)$$

Where $\theta=\omega t+\theta_0$ and ω is the reference frame rotating velocity. Therefore, the torque relation is calculated as eq.(2):

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}) \quad (2)$$

If the d axis is the same direction of the rotor flux ψr (in induction motors) or the same direction of pole flux ψp (in the PMSM motor), the vertical component of the flux fades out. Since in this method we direct the d-axis in the direction of the rotor flux, then the q axis flux will be zero. We have from the rotor voltage d-axis relationship:

$$\psi_{qr} = 0 \quad \Rightarrow \quad 0 = p\psi_{dr} + R_r i_{dr} \tag{3}$$

Because the rotor current can't be measured, then the i_{dr} current must be eliminated from the above relationship, so:

$$\psi_{dr} = L_m i_{ds} - \frac{L_r}{R_r} p\psi_{dr}$$

$$\Rightarrow \quad \psi_{dr} = \frac{L_m}{1 + p\frac{L_r}{R_r}} i_{ds} \tag{4}$$

So, in accordance with eq.(4), with controlling the ids current, can control the flux. Also, since the q axis flux is zero, the torque relation is given by eq.(5):

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\psi_{dr} i_{qs} \tag{5}$$

According to equation (5), with constant flux, torque can be controlled independently with iqs current. The ids component of the stator current can be used as a control parameter for the rotor flux ψdr. If the rotor flux is assumed fixed with the help of ids, then the iqs component plays a role of a control variable for torque. As the relationship is clear, this method depends on the engine parameters. The structure of the vector control applying on induction motor using the FOC method is shown in Fig. 1.

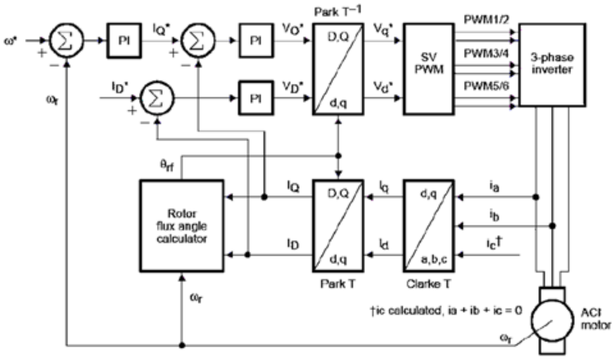

Fig. 1. Indirect vector control of induction motor by FOC [3]

In induction motors, the control is carried out in a reference frame parallel to the rotor flux vector; therefore, in order to match the reference frame with the rotor flux, the angular position of the rotor flux spatial vector must be calculated [4].

3. DIRECT TORQUE CONTROL

The classic direct torque control method was introduced in 1984 by takahashi and then in 1985 by depenbroke in Germany. The induction motor torque equation is given in eq. (6).

$$T = \frac{3}{2} . \frac{P}{2} . \overrightarrow{\psi_S} \times \overrightarrow{I_S} \tag{6}$$

where ψ_s is the stator flux, I_s is the Stator current and P is the number of motor poles. If the stator current has been written in terms of rotor and stator flux, the torque equation is obtained as eq. (7) [8-10] .

$$\overline{T_e} = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_s L_r - L_m{}^2}\overline{\psi_s} \times \overline{\psi_r}$$

$$= \frac{3}{2}\frac{P}{2}\frac{L_m}{L_s L_r - L_m{}^2}\left|\overline{\psi_s}\right| \times \left|\overline{\psi_r}\right| .\sin(\rho_s - \rho_r) \qquad (7)$$

The L_s is the stator inductance, Lr is the rotor inductance and the L_m is the mutual inductance of the rotor and stator. ρ_s and ρ_r are the stator and rotor flux angles respectively.

According to eq. (7), torque can be controlled by controlling the angle between the stator and rotor flux. Since the rotor time constant is larger than the stator, the rotor flux changes slowly in with respect to the stator flux. In fact, the angular velocity of the rotor flux can be considered constant and the motor torque is changed and controlled independently by changing the angle of the stator flux. If the arrangement and modification of the stator space vector causes the stator flux vector angle to move faster (relative to the rotor flux vector), the torque also increases with increasing angles between the rotor and stator flux. Also, if the change of the stator voltage space vector causes the stator flux vector to move more slowly than the rotor flux vector (relative to the rotor flux vector), the torque decreases by reducing the angle between the rotor and stator flux vectors. eq. (8) exists between the voltage and the Stator Flux.

$$\frac{d\psi_s}{dt} = V_s - R_s I_s \qquad (8)$$

Where R_S is the stator resistance. The DTC method only requires the stator resistance to estimate the flux and torque. If the stator resistance is also ignored, then the stator flux can be expressed as eq.(9) in terms of voltage.

$$\frac{\overrightarrow{d\psi_s}}{dt} = \overrightarrow{V_s} \qquad (9)$$

At short intervals of sampling, the eq.(10) can be considered between the space vectors of stator flux and voltage.

$$\overrightarrow{\Delta\psi_s} = \overrightarrow{V_s}.\Delta T \qquad (10)$$

Where $\Delta\Psi$ is the stator flux change vector, V_s is the stator voltage vector and ΔT is the sampling time. According to eq.(10), the vectors $\Delta\Psi$ and V_s are the same direction. Therefore, with respect to the direction of each of the six non-zero voltage vectors, the direction of the stator flux vector can be reduced or increased. In other words, by applying the appropriate voltage vector, both the stator flux vector size and angle can be changed [8]. In Fig. 2, by applying the V_s vector to the stator, the size and angle of the stator flux vector are increased.

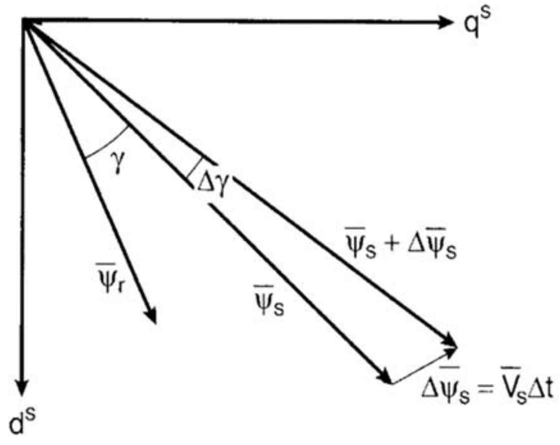

Fig. 2. The change of the stator flux vector ψs by applying the voltage vector Vs [8]

To properly correct the stator flux vector, one must know which flux vector is located in which sector and, accordingly, choose the appropriate voltage vector, so that it is possible to control the stator flux and the torque independently by applying the appropriate voltage vector. In the α-β coordinate system with stationary reference frame and at any time, the position of the stator flux is in one of the six sectors shown in Fig. 3. Also, assuming that the stator flux vector is located in the first sector, the effect of applying each of the six different voltage vectors on increasing and decreasing the flux vector and the torque is shown in Fig. 3.

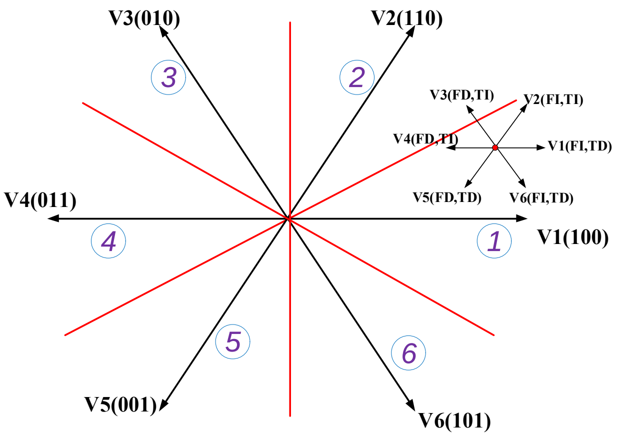

Fig. 3. Changes in the size of the flux and torque in the sector 1 According to the application of different voltage vectors [9]

3.1. Lookup table

In general, if the stator flux vector is in sector k, then applying V_{k-1}, V_k, V_{k+1} voltage vectors will increase the flux and applying the vectors V_{k+2}, V_{k-2}, V_{k+3} will reduce the flux vector magnitude. Also applying V_{k+1} and V_{k+2} voltage vectors increase torque and V_{k-1} and V_{k-2} voltage vectors reduce torque. V_k and V_{k+3} voltage vectors are not seen in torque variations, because they can increase or decrease the torque, depending on whether the flux vector is located at the first or second 30 degree of a sector. The effects of each voltage vector are summarized in Table .1:

Table.1. lookup table for direct torque control [9]

Sector k	increase	decrease
Stator flux	K, k+1, k-1	K+2, k-2, k+3
torque	K+1, k+2	k-1, k-2

3-2- Hysteresis comparator

The principles of the classical DTC method are that the appropriate voltage vector is selected based on the error between the actual and reference values of the flux and torque. The comparison between the actual and reference values of flux and torque is made in the hysteresis comparators. To compare the fluxes and torques, two-level and three-level control is used respectively. As a result, the flux error ΔΨ can have two different values and torque error Δτ can have three different values. This is stated in eq.(11) and eq.(12) [12].

$$\Delta\psi_S = \begin{cases} 1 & \text{if } \left|\psi_s^*\right| - \left|\psi_s\right| \geq \left|\text{hysteresis band}\right| \\ 0 & \text{if } \left|\psi_s^*\right| - \left|\psi_s\right| \leq -\left|\text{hysteresis band}\right| \end{cases} \tag{11}$$

$$\Delta T_e = \begin{cases} 1 & \text{if } \left|T_e^*\right| - \left|T_e\right| \geq \left|\text{hysteresis band}\right| \\ 0 & \text{if } \left|T_e^*\right| - \left|T_e\right| \quad \text{within hystersis band} \\ -1 & \text{if } \left|T_e^*\right| - \left|T_e\right| \leq -\left|\text{hysteresis band}\right| \end{cases} \tag{12}$$

The structure of the two-level flux hysteresis comparators and the three-level torque comparators are shown in Fig. 4 and Fig .5 [9-10].

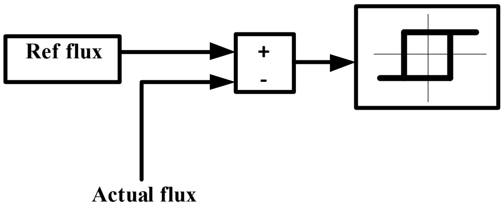

Fig. 4. Flux Hysteresis comparator [10-9]

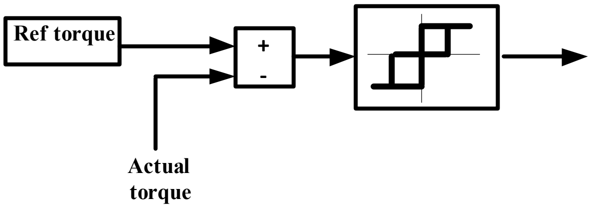

Fig. 5. Torque hysteresis Comparator

Flux and torque hysteresis bandwidth is one of the important factors in classical DTC performance. The output of the flux and torque hysteresis comparators along with the position of the stator flux is included in the table. According to the flux and torque variation table as well as the levels of hysteresis control, Table 2 can be considered as the switching Table [13,14].

Table. 2. Lookup table for selecting the appropriate voltage vector [14]

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

The sector number of stator flux vector is shown with S1 to S6. In the lookup table, according to the position of the stator flux vector and the desired target for increasing the flux and torque obtained from the hysteresis comparators, the appropriate voltage vector is selected from the lookup table and applied to the inverter. Voltage vectors V0 and V7 are selected when the torque error is within the specified range.

3. 3. Stator flux and torque Estimation

In DTC, the flux and torque values are calculated in the α-β coordinate system using Clark's transform, so no longer need to convert the three-phase abc to the three-phase dqo and not know the position of the rotor's flux.

The eq.(13) and eq.(14) are used to calculate the stator flux:

$$\psi_{s\alpha} = \int (V_{s\alpha} - R_s I_{s\alpha}) dt \qquad (13)$$

$$\psi_{s\beta} = \int (V_{s\beta} - R_s I_{s\beta}) dt \qquad (14)$$

Where R_S is the stator resistance, I_α, I_β, ψ_α and ψ_β are the stator current and flux on α and β axes respectively. Also, the magnitude and angle of flux and torque are calculated by eq.(15) to eq.(17) [10-9].

$$|\psi_s| = \sqrt{\psi_\alpha^2 + \psi_\beta^2} \qquad (15)$$

$$\square\ \psi_S = \tan^{-1}\frac{\psi_\beta}{\psi_\alpha} \qquad (16)$$

$$\tau = \psi_\alpha i_\beta - \psi_\beta i_\alpha \qquad (17)$$

The classic DTC structure is shown In Fig. 6.

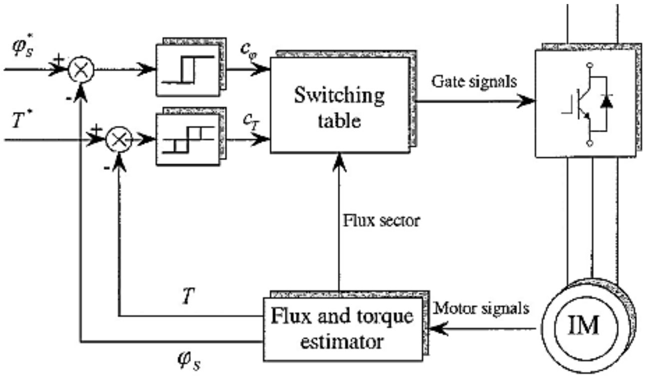

Fig. 6. Classical DTC structure [10]

As is clear from the classical DTC block diagram, the only parameter used by is the stator's resistance. In this structure, there are two distinct loops related to the estimation of the actual magnitude of the stator flux and torque, which are entered into the hysteresis comparators after comparing with the reference values. The output of the hysteresis comparators, along with the position of the stator flux, is entered into the lookup table, and the appropriate voltage vector is selected according to the position of the stator flux as well as the magnitude of the error between the flux and torque.

4. **Simulation**

The required designs for both the FOC and DTC vector control techniques applying on induction motors are shown in Fig. 7 and Fig .8.

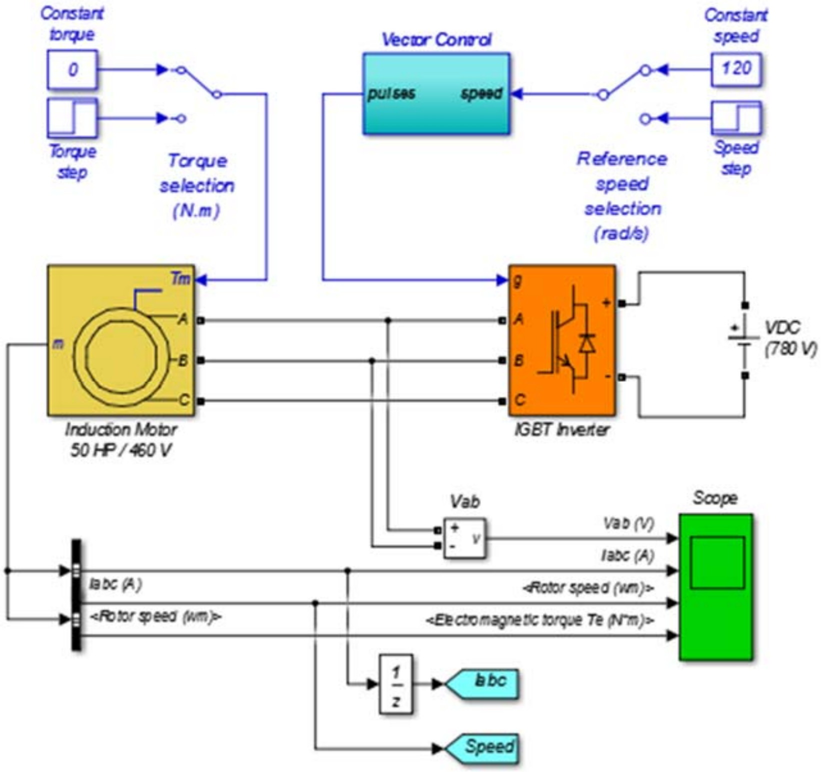

Fig. 7. Implementation of FOC in MATLAB

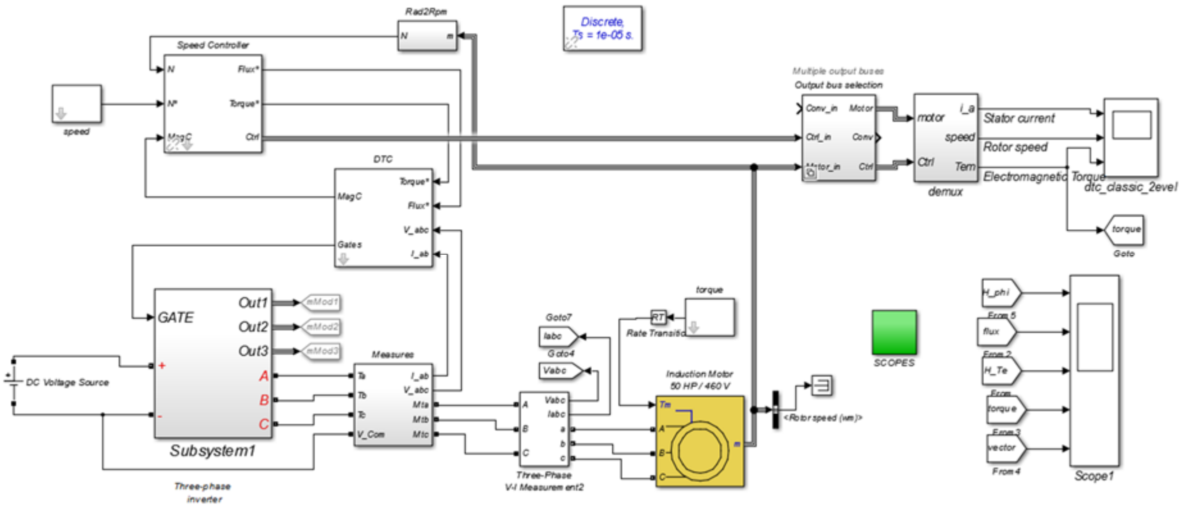

Fig. 8. Implementation of DTC in MATLAB

The induction motor of 5 horsepower, 460 V 60 Hz has a stator resistance and inductance of 0.877 ohm and 0.8 mH, the rotor resistance and inductance is 0.228 Ohms and 0.8 mH and the mutual inductance is 34.7 mH. The inverter is a two-level three-phase inverters is made of IGBT/DIODE switches and connected to a DC voltage source of 780 volts. The motor nominal flux is 0.96 Wb.

The motor is set to 300 RPM for no load speed. The stator flux variations in both DTC and FOC methods are shown in Fig. (9) and Fig .(10).

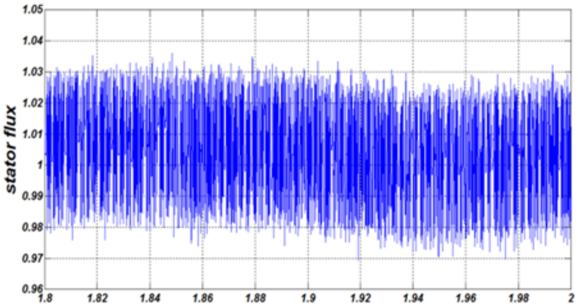

Fig. 9. Stator flux variations in DTC

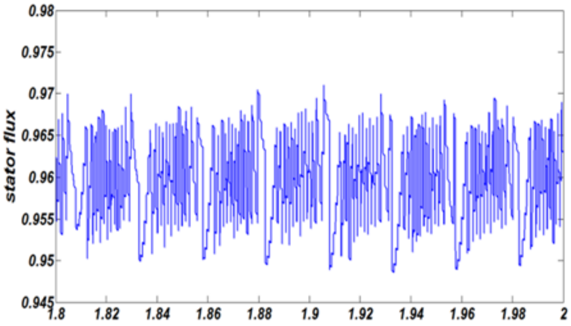

Fig. 10. Stator flux variations in FOC

As shown in Fig.(9) and Fig .(10), the stator flux in DTC method has more ripple than FOC method. The torque variation curve of the induction motor is shown in Fig. (11) and Fig. (12) in both the FOC and DTC vector control methods.

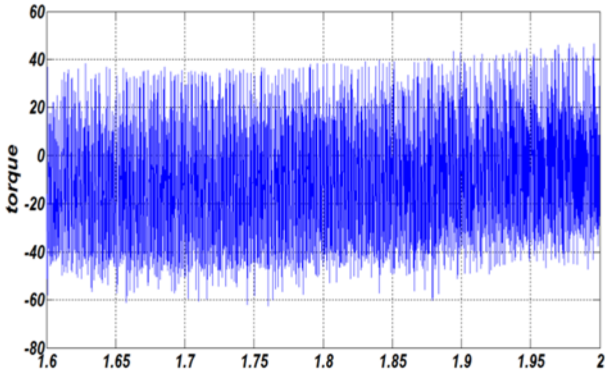

Fig.11. Torque variations in DTC method

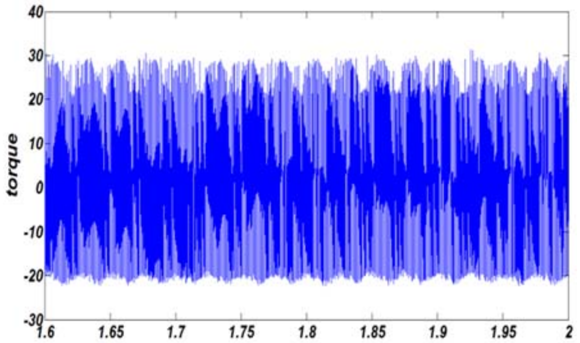

Fig. 12: Torque variations in FOC method

According to Fig.(11) and Fig .(12), the torque ripple in DTC method are greater than the torque ripple in FOC method.

5. **Conclusion**

In this paper, the performance of vector control of induction motors using field oriented control and direct torque control is described. The governing equations describe the performance of these two methods in full. In order to compare and evaluate the performance of DTC and FOC methods, simulation in MATLAB/Simulink has been performed. The simulation results indicate that the DTC method has more flux and torque ripple than FOC, but at the same time it has less sensitivity to motor parameters and also eliminates the limitations and complexity of the FOC method.

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