International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 7, No. 4, December 2016, pp. 1125~1133
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v7i4.pp1125-1133

Performance Characteristics of Induction Motor with Field Oriented Control Compared to Direct Torque Control

Hamdy Mohamed Soliman
Director of Research and Development of Driving Trains, Cairo, Egypt

Article Info

Article history:

Received May 26, 2016
Revised Oct 31, 2016
Accepted Nov 12, 2016

Keyword:

Direct torque control
Field oriented control
Induction motor
MATLAB simulink

ABSTRACT

With development of power electronics and control Theories, the AC motor control becomes easier. So the AC motors are used instead of the DC motor in the drive applications. With this development, a several methods of control are invented. The field oriented control and direct torque control are from the best methods to control the drive systems. This paper is compared between the field oriented control and direct torque control to show the advantages and disadvantages of these methods of controls. This study discussed the effects of these methods of control on the total harmonic distortion of the current and torque ripples. This occurs through study the performance characteristics of the AC motor. The motor used in this study is an induction motor. This study is simulated through the MATLAB program.

Corresponding Author:

Hamdy Mohamed Soliman,
Director of Research and Development of Driving Trains, Cairo, Egypt.
Email: hamdysoliman123@gmail.com

1. INTRODUCTION

In the past, the DC motors used in industrial applications to get accurate speed, fast dynamic response and high dynamic performance characteristics nearer to zero speed but they suffer from some problems such as large size, heavy Wight, frequent maintenance, high expensive and sparking due to brushes. With the development of power electronics and control theories, the induction motor replaced the DC motor to get rid from the drawbacks of the DC motor i.e. the induction motor is the most common used motor in the industrial applications this is because it is rugged strcture, low cost, low maintenance, high operating life and high effiecency [1-2]. The performance of the induction motor in the drive system depending upon the motor control and current control method or voltage control in power converter. The current control method is preferable this is because it is simple. The quality control of this method depending upon the quality of the waveform which generated. To get good power waveform this depends upon the switching of inverter, modulation index and pulse width modulation (PWM). Some methods of current control such as scalar control is suffer from complicated coupling nonlinear dynamic performance. This problem can be solved by using field oriented control (FOC) or by direct torque control (DTC) [3-4]. This paper is used to comparing between these methods of control (FOC and DTC). This occurs through the simulation theses controls with using the MATLAB program. The simulation studied the following cases

1. Motor operating at rated conditions.
2. Sudden applied and removal the load at rated speed.
3. Reversing speed at full load.

This paper is organized as the follows, 1-introduction, 2-mathematical model of induction motor, 3-field oriented control, 4-direct torque control, 5-simulation results and 6- conclusion.

2. MATHIMATICAL MODEL OF INDUCTION MOTOR

The mathematical model of induction motor can be written as

$$v_{qse} = r_s i_{qse} + \frac{d\psi_{qse}}{dt} + \omega_e \psi_{dse} \tag{1}$$

$$v_{dse} = r_s I_{dse} + \frac{d\psi_{dse}}{dt} - \omega_e \psi_{qse} \tag{2}$$

$$0 = r_r I_{qre} + \frac{d\psi_{qre}}{dt} + (\omega_e - \omega_r)\psi_{dre} \tag{3}$$

$$0 = r_r I_{dre} + \frac{d\psi_{dre}}{dt} - (\omega_e - \omega_r)\psi_{qre} \tag{4}$$

$$\psi_{qse} = L_s I_{qse} + L_m I_{qre} \tag{5}$$

$$\psi_{dse} = L_s I_{dse} + L_m I_{dre} \tag{6}$$

$$\psi_{qre} = L_r I_{qre} + L_m I_{qse} \tag{7}$$

$$\psi_{dre} = L_r I_{dre} + L_m I_{dse} \tag{8}$$

$$T_e = 3\frac{P}{4}\frac{L_m}{L_r}(\psi_{dre} I_{qse} - \psi_{qre} I_{dse}) \tag{9}$$

$$J\frac{d\omega_r}{dt} = T_e - T_L - B\omega_r \tag{10}$$

Where v_{qse} and v_{dse} are the q and d axis stator voltage, I_{qse} and I_{dse} are the q and d axis stator current, I_{qre} and I_{dre} are the q and d axis rotor current, ψ_{qse} and ψ_{dse} are the q and d axis stator flux, ψ_{qre} and ψ_{dre} are the q and d axis rotor flux, r_s and r_r are the stator and rotor resistance, L_s, L_r and L_m are the stator, rotor and magnetizing inductances, P is the number of poles, T_e,T_L are the electromagnetic torque and load torque, $\frac{d}{dt}$ is a derivative, ω_r is a rotor speed, B is a friction viscous and J is a moment of inertia.

3. FIELD ORIENTED CONTROL

The field oriented control introduced for the first time at the hands of Blashka in 1971 as an alternative to bring the induction motor instead of the DC motor in industrial applications that required high dynamic performance [5]. In FOC, the space phasor of the stator current is decoupled into two components torque current component and flux current component. The flux current control is aligned with the rotor flux as shown in Figure 1. To implement that, the position and magnitude of the rotor flux are required and this can be done directly by using sensor to measure the rotor flux or indirectly by estimating the rotor flux. In this paper the rotor flux is estimated by indirect method [6-8]. This means that, the d-axis rotor flux is equal to the rotor flux and the q-axis rotor flux becomes zero so the rotor flux can be calculated as

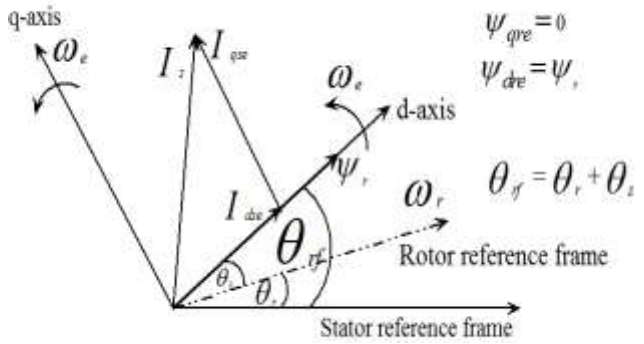

Figure 1. Phasor Diagram of Field Oriented Control

$$\psi_r = \frac{L_m}{1+T_r \frac{d}{dt}} I_{dse} \tag{11}$$

In the estimated model, the reference rotor flux can be deduced from lookup table designed in MATLAB program depending upon the rotor speed. With aid of the above equation the estimating d-axis stator current can be calculated as

$$I_{dse}^{*} = (1+T_r \frac{d}{dt}) \frac{\psi_r^{*}}{L_m} \tag{12}$$

The rotor flux angle can be calculated as the sum of rotor position and rotor field position referred to the rotor as the following equation

$$\begin{aligned} \theta_{rf} &= \theta_r + \theta_s \\ \theta_s &= \frac{L_m}{T_r \psi_r^{*}} I_{dse} \end{aligned} \tag{13}$$

And the motor torque becomes

$$T_e = 3 \frac{P}{4} \frac{L_m}{L_r} \psi_r I_{qse} \tag{14}$$

This torque can be deduced from the PI torque current controller. With aid this torque, the estimated torque current component (I_{qse}) can be deduced from the above equation as

$$I_{qse}^{*} = \frac{1}{3} \frac{4}{P} \frac{L_r}{L_m \psi_r^{*}} T_e \tag{15}$$

With help of torque current component (I_{qse}^{*}), flux current component (I_{dse}^{*}) and position of rotor flux (θ_{rf}), the estimating 3 phase stator current can be calculated. The 3 phase stator current estimated are compared to the actual three phase current which measured by sensor to switching frequency of inverter as shown in Figure 2. This Figure shows the details of the indirect field oriented control for induction motor.

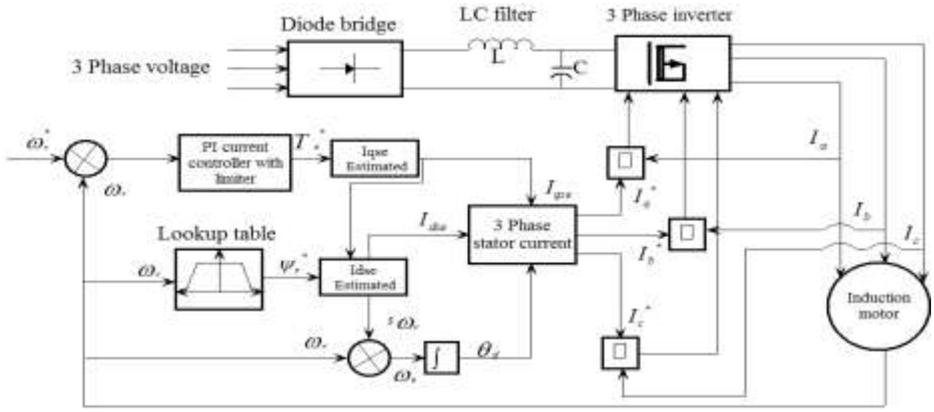

Figure 2. Stigmatic Diagram of the Indirect Field Oriented Control of Induction Motor

4. DIRECT TORQUE CONTROL

The direct torque control introduced for the first time at the hands of Takahashi and Noguchi in 1986. The direct torque control (DTC) is said to be one of the future ways of controlling the AC machine in four quadrants. In DTC it is possible to control directly the stator flux and the torque by selecting the appropriate inverter state. DTC main features are direct control of flux and torque, indirect control of stator currents and voltages, approximately sinusoidal stator fluxes and stator currents, and High dynamic performance even at stand still [9-12]. DTC have several advantages if it is compared to FOC as, Decoupled control of torque and flux, Absence of co-ordinate transforms, Absence of voltage modular block, Absence of mechanical transducers, Current regulator, PWM pulse generation, PI control of flux and torque and co-ordinate transformation is not required, Very simple control scheme and low computational time, and Reduced parameter sensitivity and Very good dynamic properties as well as other controllers such as PID for motor flux and torque, and Minimal torque response time even better than the VCs [11-12]. However, some disadvantages are also present such as: Possible problems during starting, Requirement of torque and flux estimators, implying the consequent parameters identification, and Inherent torque and stator flux ripple [9-13]. Although, some disadvantages are: High torque ripples and current distortions, Low switching frequency of transistors with relation to computation time, Constant error between reference and real torque [12-13].

The stigmatic diagram of the DTC is used here can be seen in Figure 3. In this stigmatic diagram; the reference rotor speed is compared to the measure of the motor speed and the error is introduced to PI controller to deduce the torque command. The torque command is compared to the estimated torque and the error is introduced to the three level hysteresis controller. Also the stator flux command is compared to the estimated stator flux and the error is introduced to the two level hysteresis controller. With aid the two hysteresis controllers, the switching is occurred and the output of inverter voltage is applied on the motor. The switching Table due to hysteresis control of the flux and torque can be seen in Table 1.

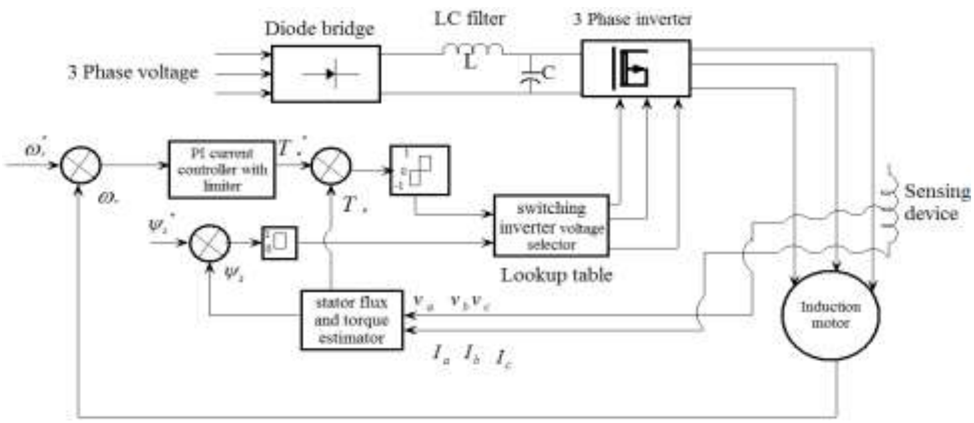

Figure 3. Stigmatic Diagram of the Direct Torque Control of Induction Motor

Table 1. The Switching Vector to Drive the Inverter

Flux comparator	Torque comparator	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6
1	1	V2	V3	V4	V5	V6	V1
1	0	V7	V0	V7	V0	V7	V0
1	-1	V6	V1	V2	V3	V4	V5
0	1	V3	V4	V5	V6	V1	V2
0	0	V0	V7	V0	V7	V0	V7
0	-1	V5	V6	V1	V2	V3	V4

5. SIMULATION RESULTS

The simulation results for FOC and DTC are discussed here, the cases of study are for induction motor which has the data in Table 2. The cases of study, when the motor starting with full load at rated speed, at sudden applied and removal the load and at reversing speed.

5.1. First Case of Study

In this case, the motor is operated at rated conditions with FOC and with DTC. Figure 4 shows the motor torque with FOC and Figure 5 shows the motor torque with DTC where it is found that. The motor torque is less ripple with FOC if it is compared to DTC. The over shooting of the torque is higher with FOC. The motor torque is reached steady state in shorter time with FOC if it is compared to DTC.

Figure 6 shows the motor speed with FOC and Figure 7 shows the motor speed with DTC where it is found that. The motor reaches the rated speed with FOC in faster than that time of the DTC. Figure 8 shows the stator current with FOC and Figure 9 shows the stator current with DTC where it is found that. The stator current is less ripple with FOC if it is compared to DTC. The starting current is higher with DTC. The stator current is reached steady state in shorter time with DTC if it is compared to FOC.

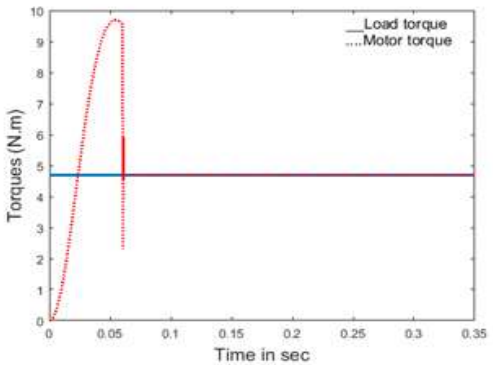

Figure 4. Torque with Field Oriented Control

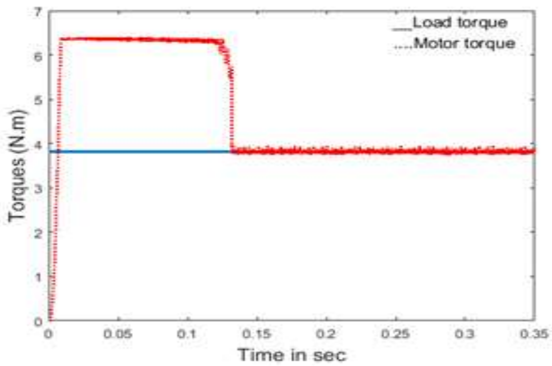

Figure 5. Torque with Direct Torque Control

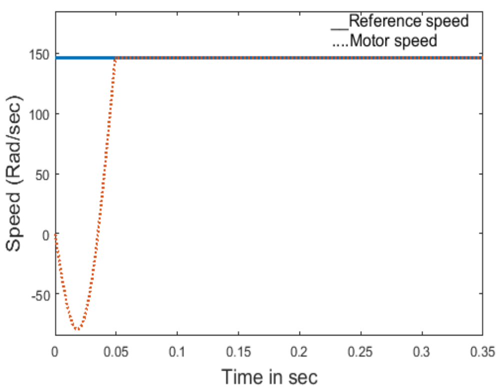

Figure 6. Speed with Field Oriented Control

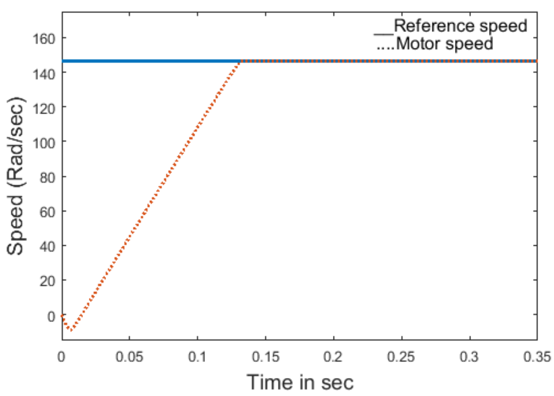

Figure 7. Speed with Direct Torque Control

5.2. Second Case of Study

In this case, the motor is starting without load at 0.15 sec the load is suddenly applied and at 0.35 the load is suddenly removed for FOC and DTC. Figure 10 shows the motor torque with FOC and Figure 11 shows the motor torque with DTC where it is found that; the motor torque is less ripple with FOC if it is compared to DTC. The over shooting of the motor torque is approximately equal in the two methods of control. The motor torque is reached steady state in shorter time with FOC if it is compared to DTC.

Figure 12 shows the motor speed with FOC and Figure 13 shows the motor speed with DTC where it is found that. The motor reaches the rated speed with FOC in faster than that time of DTC and the effect of sudden applied load and removal the load can be neglected with DTC. Figure 14 shows the stator current with FOC and Figure 15 shows the stator current with DTC where it is found that. The stator current is less ripple with FOC if it is compared to DTC. The starting current is higher with DTC.

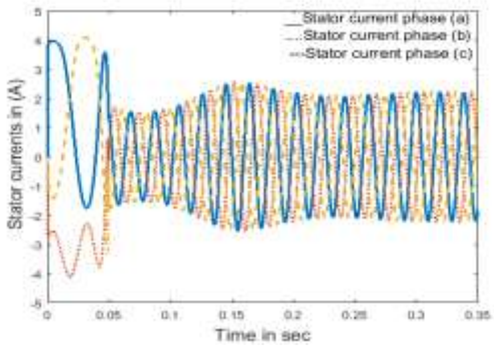

Figure 8. Stator Current with Field Oriented Control

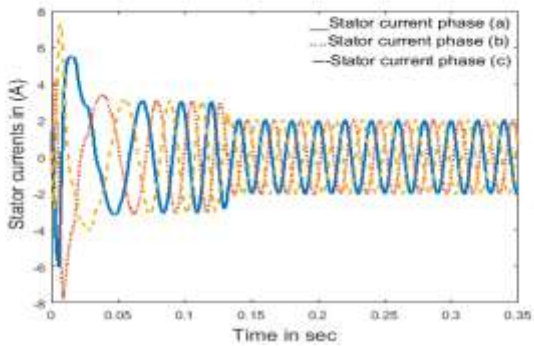

Figure 9. Stator Current with Direct Torque Control

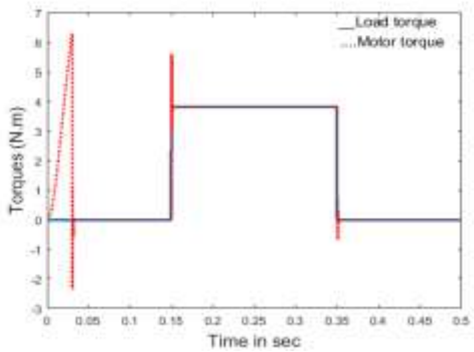

Figure 10. Torque with Field Oriented Control

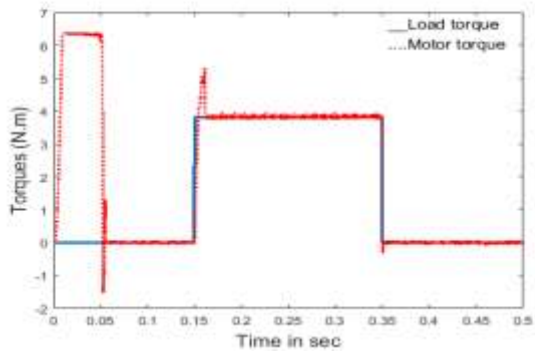

Figure 11. Torque with Direct Torque Control

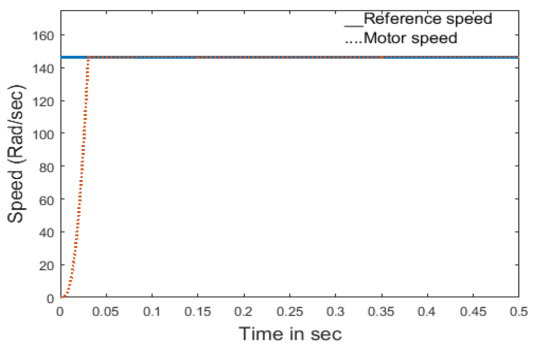

Figure 12. Speed with Field Oriented Control

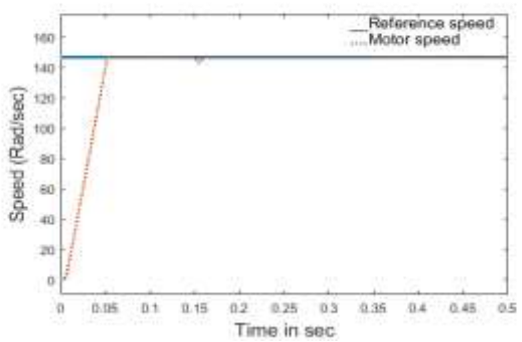

Figure 13. Speed with Direct Torque Control

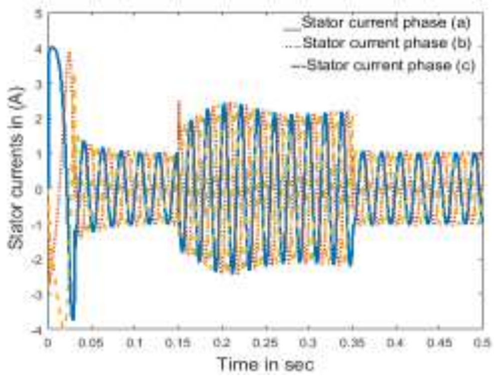

Figure 14. Stator Current with Field Oriented Control

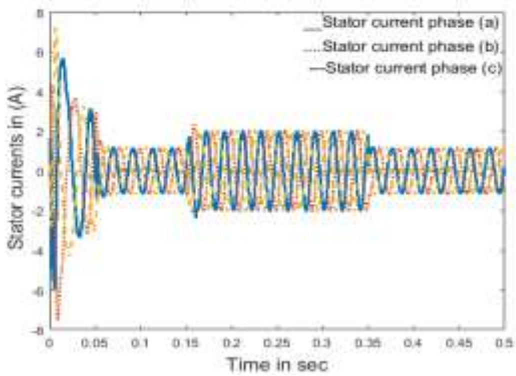

Figure 15. Stator Current with Direct Torque Control

5.3. Third Case of Study

In this case, the motor is operated at rated conditions at 0.25 sec the motor speed is suddenly reverse for FOC and DTC. Figure 16 shows the motor torque with FOC and Figure 17 shows the motor torque with DTC where it is found that.

The motor torque is less ripple with FOC if it is compared to DTC. The over shooting of the torque is higher with FOC. The motor torque is reached steady state in shorter time with FOC if it is compared to DTC. At reversing speed, the motor torque is more effect with DTC i.e. the over shooting in the motor is higher in reverse direction with DTC. Figure 18 shows the motor speed with FOC and Figure 19 shows the motor speed with DTC where it is found that. The motor reaches the rated speed with FOC in faster than time of DTC.

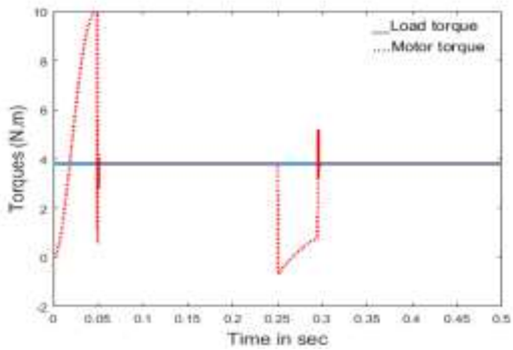

Figure 16. Torque with Field Oriented Control

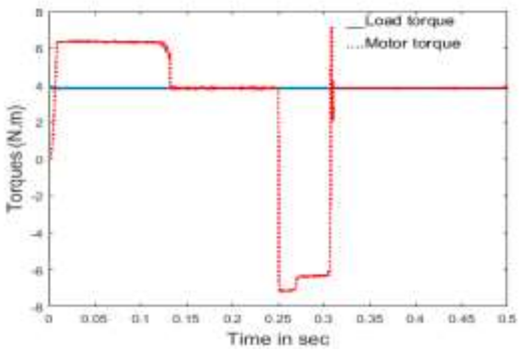

Figure 17. Torque with Direct Torque Control

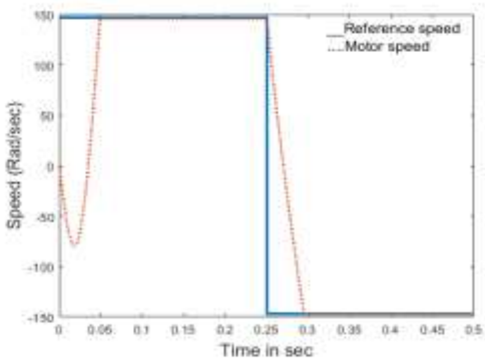

Figure 18. Speed with Field Oriented Control

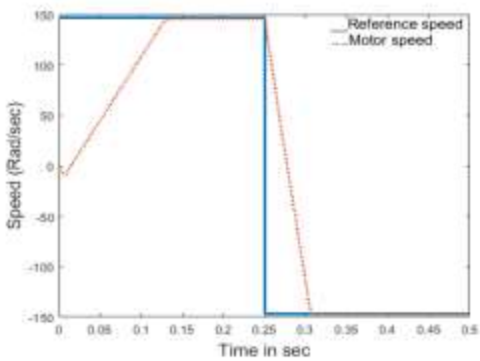

Figure 19. Speed with Direct Torque Control

Figure 20 shows the stator current with FOC and Figure 21 shows the stator current with DTC where it is found that. The stator current is less ripple with FOC if it is compared to DTC. The starting current is higher with DTC. The stator current is reached steady state in shorter time with DTC if it is compared to FOC. When motor speed is reversing, the stator current is reversing in the two methods of control. The stator current with DTC is more effecting by reversing speed if it is compared to FOC

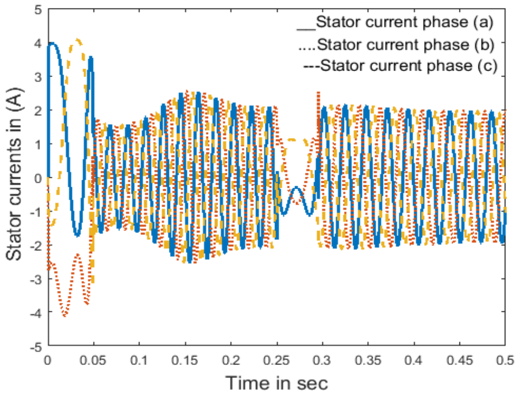

Figure 20. Stator current with field oriented control

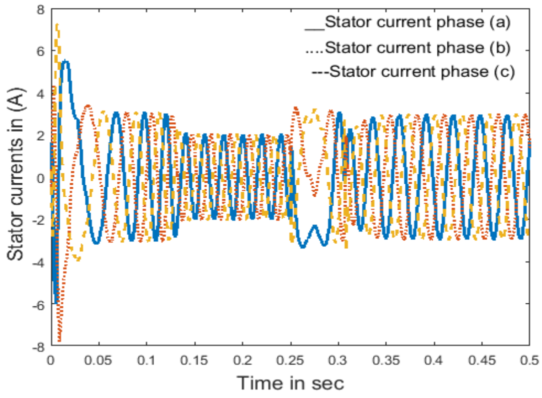

Figure 21 Stator current with direct torque control

6. CONCLUSION

The comparing between the FOC and the DTC is held. The simulation shows that, the torque ripples and total harmonics is less with FOC if it is compared to DTC. The motor speed and motor torque reach the steady state with FOC is faster than that time with DTC. The over shooting of the starting torque is the highest with FOC if it is compared to DTC. The motor current reaches to steady state in faster time with DTC if it is compared to FOC. With these models (FOC and DTC) the effect of sudden applied and removal the load can be neglected. The motor torque and stator current in case of DTC is the more effecting by reversing speed if it is compared to FOC.

Table 2. The Motor Data

Line to line voltages	380V
Full load current (I_f)	1.47A
Rotor speed (n_r)	1400 R.P.M
Pole pairs	2
Full load torque (T_f)	3.82 N.m
Power factor (pf)	0.8
Stator resistance	13 Ohm
Stator reactance	10.5 Ohm
Magnetizing reactance	231 Ohm
Rotor resistance	2.25S+12.35 Ohm
Rotor reactance	-3.694S+19.2643 Ohm
Output power	0.75 hp
T_s/T_f	2.33
T_{max}/T_f	2.62
I_s/I_f	4.22
Efficiency	0.72

REFERENCES

[1] M.D. Murphy, F.G Turnball: Power electronic control of A.C motors, Pergamon press, 1986.
[2] Bose B.K: Power Electronics and Variable Frequency Drives, *IEEE* Press, 1997.
[3] W.B Rosink: *Analogue control system for A.C motor with PWM variable speed*, in proceedings of Electronic Components and Application, Vol. 3, No.1, November 1980, pp. 6-15.
[4] B.G. Starr, J.C.F. Van Loon: *LSI circuit for AC motor speed control* in proceedings of Electronic Components and aplication Vol. 2, No. 4, August 1980, pp. 219-229.
[5] F. Blaschke: "The Principle of Field Orientation Applied to the New Transvector Closed-Loop Control System for Rotating Field Machines", *Siemens-Rev.*, vol. 39, 1972, pp. 217–220.
[6] W. Leonhard: "*Field Orientation for Controlling AC Machines Principle and Application*", A tutorial, IEE conf. on power electronic variable speed drives conf. pub. No. 291, London, 1988 pp. 277-282.

[7] R. Krishnan, A.S. Bhardawaj (1991), "A Review of Parameter sensitivity and adaptation in Industrial vector controlled Induction motor drive system", *IEEE Trans. on Power Electronics*, Vol. 6, No. 4, 1991 pp. 219-225.

[8] Hamid.A. Toliyat, Emil Levi, Mona Raina "A Review of RFO Induction motor parameter Estimation Technique", *IEEE Transaction on Energy Conversions*, Vol. 18, No. 2, 2003, pp 356-365.

[9] G.S. Buja and M.P. Kazmierkowski, Direct torque control of PWM inverter-fed ac motors—a survey, *IEEE IE Trans.*, vol. 51, pp. 744–757, August 2004.

[10] P. Marino, M.D. Incecco and N.Visciano, A comparison of Direct Torque Control Methodologies for Induction Motor, *IEEE trans*. 2001.

[11] G. Buja *et al.*, Direct torque control of induction motor drives, IEEE ISIE Conf. Rec., pp. TU2–TU8, 1997.

[12] Burak Ozpineci, L.M. Tolbertr, Simulink Implementation of Induction Machine Model-A modular approach, *IEEE Trans*. 2003.

[13] Siva Ganesh Malla, "*A Review on Direct Torque Control (DTC) of Induction Motor: with Applications of Fuzzy*", International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT), pp. 132 – 142, 2016.

BIOGRAPHY OF AUTHOR

Dr. Hamdy Mohamed Soliman was born in Cairo-Egypt on 26 December 1970, He received B. Sc. in Electrical Power and Machine Engineering from Helwan University in 1993, master of science in area of electrical machine and drive systems. Master of science is from Benha University and PhD Degree from Cairo University, Giza, Egypt in 2016. The area of PhD is electrical machines and drives. He is a director of development and research of train units in Egyptian company metro. His current research interests include power electronics, motor controls and drive systems.