Research Journal of Applied Sciences, Engineering and Technology 5(15): 3934-3940, 2013
DOI:10.19026/rjaset.5.4455
ISSN: 2040-7459; e-ISSN: 2040-7467
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Submitted: September 10, 2012 Accepted: October 19, 2012 Published: April 25, 2013

Research Article

High Performance of Space Vector Modulation Direct Torque Control SVM-DTC Based on Amplitude Voltage and Stator Flux Angle

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Abstract: Various aspects related to controlling induction motor are investigated. Direct torque control is an original high performance control strategy in the field of AC drive. In this proposed method, the control system is based on Space Vector Modulation (SVM), amplitude of voltage in direct- quadrature reference frame (d-q reference) and angle of stator flux. Amplitude of stator voltage is controlled by PI torque and PI flux controller. The stator flux angle is adjusted by rotor angular frequency and slip angular frequency. Then, the reference torque and the estimated torque is applied to the input of PI torque controller and the control quadrature axis voltage is determined. The control d-axis voltage is determined from the flux calculator. These q and d axis voltage are converted into amplitude voltage. By applying polar to Cartesian on amplitude voltage and stator flux angle, direct voltage and quadratures voltage are generated. The reference stator voltages in d-q are calculated based on forcing the stator voltage error to zero at next sampling period. By applying inverse park transformation on d-q voltages, the stator voltages in α and β frame are generated and apply to SVM. From the output of SVM, the motor control signal is generated and the speed of the induction motor regulated toward the rated speed. The simulation Results have demonstrated exceptional performance in steady and transient states and shows that decrease of torque and flux ripples is achieved in a complete speed range.

Keywords: Amplitude voltage, Direct Torque Control (DTC), Space Vector Modulation (SVM), stator flux angle

INTRODUCTION

Direct Torque Control (DTC) of Induction Machines (IM) is an influential control technique for motor drive .It offers high performance in terms of ease in control and fast electromagnetic torque response. Implementation of DTC is based on torque and stator flux hysteresis comparators. It is widely known to produce a quick and fast response in AC drives.

DTC based on Space Vector Modulation (SVM) offers high-quality steady state and active performance by a reduction in phase current distortion with fast response of torque as reported by Domenico *et al*. (2000). However, this technique has a limitation in computationally intensive. Other researchers have been performed to find different solutions that facilitate the induction motor control to have precise, tough and speedy torque response as reported by Kennel *et al*. (2003) and Khanna *et al*. (2009). Alternatively, Space Vector Modulation (SVM) modulator is incorporated with direct torque control for induction motor drive as shown in report of Buja *et al*. (1998) to provide constant switching frequency. Another approach to DTC of IM was obtainable by Qu *et al*. (2010). In this case, the inverter switching for overcoming the disadvantage of the conventional DTC is voltage modulation application replacing look-up table of the voltage vector selection on the basis of 2-level inverter. DTC-SVM control is based on deadbeat for constant control frequency. This needed neither a raise of the sampling frequency, nor a high frequency dither. By best selection of the space voltage vectors in each sampling period, DTC recorded successful control of the stator flux and torque as reported by Yen and Jian (2001). Many domestic and foreign scholars have put forward a lot of solutions. Morales-Caporal and Pacas (2008) proposed method for control torque and flux with no deadbeat strategy. There are also many variations on conventional DTC such as predictive DTC which show evolved PDTC theories for induction motor as mentioned by Pacas and Weber (2005). The complete system is multifaceted and requirements different voltage vectors in different speed. Ryu *et al*. (2006) proposed a unified flux and torque control method for DTC-based induction motor drives and the outcome obtained showed that the planned algorithm reduces the flux and torque ripples. In this case, the look-up table in the DTC is replaced by a minimum-

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distance vector selection scheme to decrease the flux and torque ripples over a fixed sampling period. Li *et al*. (2010) and Zhifeng *et al*. (2010) presented different solutions contain DTC with SVM for finest stator flux estimator and high speed operation. Direct torque control based on fuzzy logic and neural network for decoupled stator flux and torque control also this method give good performance and minimize torque ripple as proposed by Romeral *et al*. (2003) and Mengjia *et al*. (2004).

This study proposes a high transient performance, toughness and minimize steady state -torque ripple for direct torque control based on space vector modulation, stator flux angle and amplitude of voltage in direct-quadrature reference frame. Simulation results demonstrate the feasibility and validity of the proposed SVM-DTC system by successfully accelerating system response by reduce torque and flux ripple, achieve fixed switch frequency and improving system performance.

THEORETICAL BACKGROUND

Model of induction motor: The induction motor model can be expressed in the d-q fixed reference frame by the following Eq. (1) to (6):

$$V_{sdq} = R_s\, i_{sdq} + \frac{d}{dt}\psi_{sdq} - jW_g\, \psi_{sdq} \tag{1}$$

$$0 = R_r\, i_{rdq} + \frac{d}{dt}\psi_{rdq} - j(w_g - w_r)\psi_{rdq} \tag{2}$$

$$\psi_{sdq} = l_s i_{sdq} + l_m i_{rdq} \tag{3}$$

$$\psi_{rdq} = l_r i_{rdq} + l_m i_{sdq} \tag{4}$$

$$T_e = \frac{3p}{2} L_m(\psi_{sd}\, i_{sq} - \psi_{sq}\, i_{sd}) \tag{5}$$

$$T_e - T_l = J\frac{d}{dt}w_m + Bw_m \tag{6}$$

where,

w_g, w_r, w_m	:	Generic reference system, rotor electrical, rotor mechanical speed
R_s, R_r	:	Stator and rotor resistances
L_s, L_r, L_m	:	Stator , rotor and mutual inductances
ψ_{sdq}	:	The stator flux in d-q frame
ψ_{rdq}	:	Rotor flux in d-q frame
i_{sdq}, i_{rdq}	:	Stator and rotor currents in d-q fra
P	:	Number of poles
T_e and T_L	:	Motor and load torque
B, J	:	Friction coefficient and inertia of the system

The equivalent circuit corresponding to these equations is illustrates in Fig. 1.

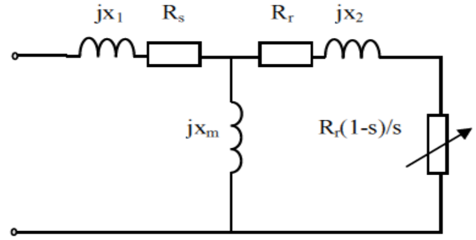

Fig. 1: Equivalent circuit of induction motor

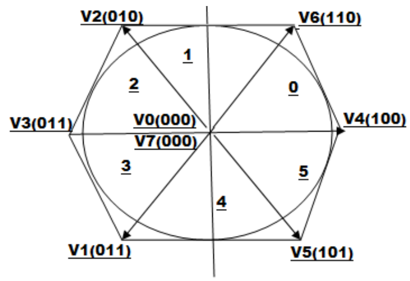

Fig. 2: Space vector diagram

Space Vector Modulation (SVM): Space vector modulation is an algorithm for the control of Pulse Width Modulation (PWM). It is used for the production of Alternating Current (AC) waveforms. There are different variations of SVM that result in different quality and computational requirements. SV PWM refers to a special method of determining the switching sequence of the upper three power transistors of a three-phase VSI Mahendran and Gurusamy (2011). It has been shown to produce less harmonic distortion in the output voltages or currents in the windings of the motor load. The SV PWM has been playing pivotal and practical role in power conversion. It is using space vector concept to compute the duty cycle of the switches which is essential implementation of digital control theory of PWM modulators. All Space Vector Modulation (SVM) techniques use a set of vectors that are defined as instantaneous space-vectors of the voltage and currents at the input and output of the converter. These vectors are produced by the different switching states that the converter is able of generating. The diagram of space vector is shown in Fig. 2.

The three phase voltage:

$$V_{AO}(t) + V_{BO}(t) + V_{CO}(t) = 0 \tag{7}$$

By using Clark transformation ((V_{abc} to $V_{\alpha\beta}$)

$$V_\alpha(t) = \frac{2}{3}\left[V_{AO}(t)\cos(0) + V_{B0}(t)\cos(\tfrac{2\pi}{3}) + V_{CO}(t)\cos(\tfrac{4\pi}{3})\right] \tag{8}$$

$$V_\beta(t) = \frac{2}{3}\left[V_{AO}(t)\sin(0) + V_{B0}(t)\sin(\tfrac{2\pi}{3}) + V_{CO}(t)\sin(\tfrac{4\pi}{3})\right] \tag{9}$$

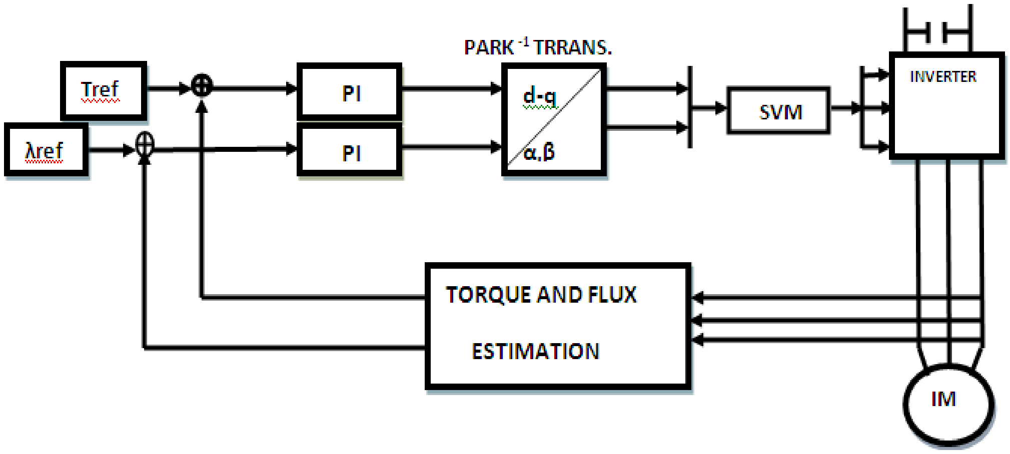

Fig. 3: DTC-SVM scheme

$$V(t) = V_\alpha(t) + V_\beta(t) \quad (10)$$

$$V(t) = \frac{2}{3}[V_{AO}(t)\, e^{j0} + V_{B0}(t)e^{j2\pi/3} + V_{co}(t)e^{j4\pi/3} \quad (11)$$

where,

$$e^{jx} = \cos(x) + j\sin(x) \quad (12)$$

$$V_{AO}(t) = \frac{2}{3} V_d \quad (13)$$

$$V_{BO}(t) = -\frac{1}{3} V_d \quad (14)$$

$$V_{CO}(t) = -\frac{1}{3} V_d \quad (15)$$

$$V_k = \frac{2}{3} V_d\, e^{j(k-1)\pi/3} \quad (16)$$

$$V_1 = \frac{2}{3} V_d\, e^{j\theta}, K = 1, 2, \ldots, 6 \quad (17)$$

The main objective of SVM is to approximate the reference voltage by using the eight switching pattern (V_0 to V_7). The equations (7 to 17) can be used to develop space vector modulation algorithm.

Direct torque control: Direct flux and torque control with Space Vector Modulation (DTC-SVM) schemes are proposed in order to develop the classical DTC. The type of DTC-SVM strategy depends on the applied flux and torque control algorithm as shown in Fig. 3. Basically, the controllers determine the essential stator voltage vector and then it is realized by space vector modulation technique.

The traditional DTC algorithm is based on the instantaneous values and directly intended the digital control signals for the inverter. The control algorithm in DTC-SVM methods are based on average values but the switching signals for the inverter are calculated by space vector modulator. This is main difference between classical DTC and DTC-SVM control as reported by Brahim *et al*. (2011).

PROPOSED METHOD

The proposed method of Direct Torque Control (DTC) using space vector modulation (SVM) is shown in Fig. 4. It can be noted that there is an evident difference between the simulation model in this new control system technique for induction motor and classical DTC. This proposed method based on space vector modulation, amplitude voltage in d-q reference frame and stator flux angle. The voltages (V_d,V_q) and stator angle are used as a reference signals in the space vector modulation. Amplitude voltage is based on both PI torque controller and PI flux controller to obtain voltage V_q ,V_d, respectively .The procedure to execute the model proposed in this study can be explained as follow:

The output of PI torque controller is the voltage in quadrature reference frame as shown:

$$V_{sq} = k_p[\Delta T_e + \frac{1}{T_i}\int \Delta\, T_e\, dt] \quad (18)$$

$$\Delta T_e = T_{ref} - T_{est} \quad (19)$$

From PI flux controller, voltage in direct reference frame can be expressed as shown:

$$V_{sd} = k_p[\Delta\lambda_s + \frac{1}{T_i}\int \Delta\, \lambda_s\, dt] \quad (20)$$

$$\Delta\lambda_s = \lambda_{ref} - \lambda_{est} \quad (21)$$

$$V_s = V_{sd} + jV_{sq} \quad (22)$$

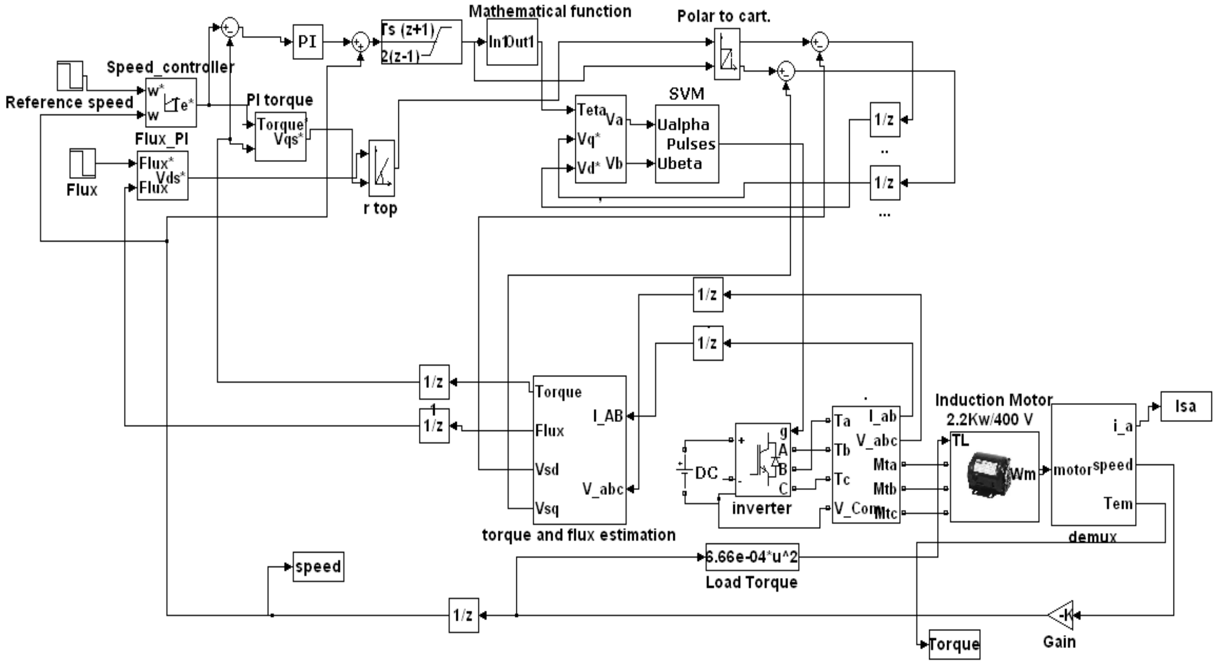

Fig. 4: Simulation of proposed SVM-DTC

Amplitude voltage can be obtained by Using Cartesian to polar as shown below:

$$|V_s| = \sqrt{(V_{sd})^2 + (V_{sq})^2} \quad (23)$$

where,
λ_{ref}, λ_{est} : Reference and estimation flux respectively
T_{ref}, T_{est} : Reference and estimation torque respectively

The stator flux angle is based on the relationship between error of torques and stator angular frequency. The slip angular frequency is the output of PI torque controller and it can be written as:

$$w_{si} = k_p[\Delta \check{T}_e + \frac{1}{T_i}\int \Delta \check{T}_e \, dt] \quad (24)$$

Stator angular frequency which is obtained by adding slip angular frequency with rotor angular frequency and can be expressed as:

$$w_s = w_{si} + w_r \quad (25)$$

Stator flux angle can be obtained by integrating of stator angular frequency:

$$\rho s = \int w(s) \, dt \quad (26)$$

By apply polar to Cartesian on both amplitude voltages in Eq. (23) and stator flux angle in Eq. (26), stator voltages in direct and quadrature reference frame are generated as:

$$V_{sd1} = |V_s| \cos\rho_s \quad (27)$$

$$V_{sq1} = |V_s| \sin\rho_s \quad (28)$$

The error voltage in d-q reference frame can be derive by subtracting the voltages of stator flux estimation from the voltages above in Eq. (27) and (28) as shown below:

$$\Delta V_{sd} = V_{sd1} - V_{sd(estimation)} \quad (29)$$

$$\Delta V_{sq} = V_{sq1} - V_{sq(estimation)} \quad (30)$$

$$V_{sd(new)} = \Delta V_{sd} + R_s \, i_{sd} \quad (31)$$

$$V_{sq(new)} = \Delta V_{sq} + R_s \, i_{sq} \quad (32)$$

By using inverse park transformation on the Eq. (31) and (32), voltages ($V_{s\alpha}$, $V_{s\beta}$) in alpha ,beta reference frame are generated and apply to SVM .

RESULTS AND DISCUSSION

In order to verify the proposed SVM-DTC scheme, simulations on an induction motor derive system are carried out. For the simulation, 3-phase Y-connected, 2.2 kW, 4-pole, 420V, 5.2A, 50Hz and 150 (rad/sec) induction motor AC drive system is used. The rated parameters of induction motor are Rs = 2.5 Ω, Rr = 2.4 Ω and, Lm = 0.085mH. Reference flux is 0.9Wb and the reference torque is the output of speed regulator with sampling time period of 50 µs. The simulation

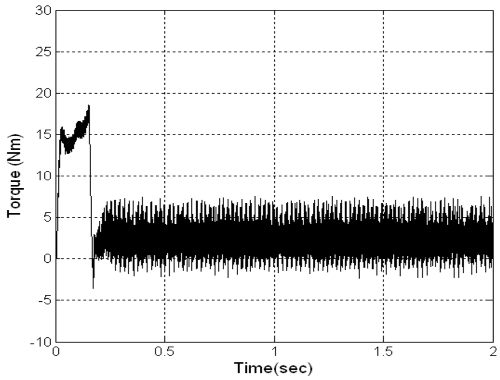

Fig. 5: Electromagnetic torque in Classical DTC

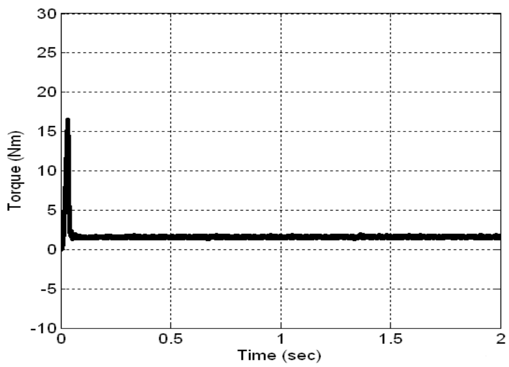

Fig. 6: Electromagnetic torque in SVM-DTC

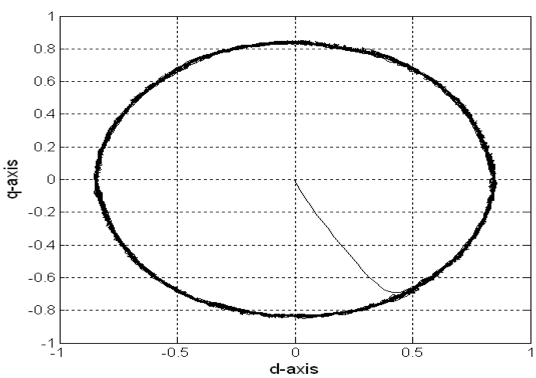

Fig. 7: Stator flux in classical DTC

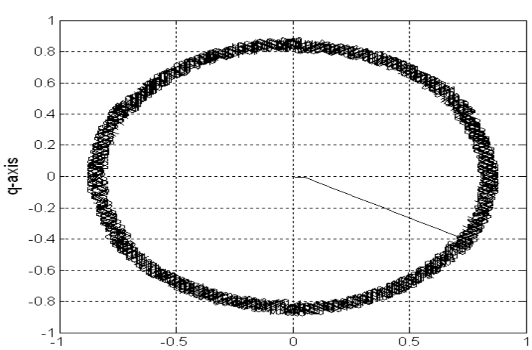

Fig. 8: Stator flux in SVM-DTC

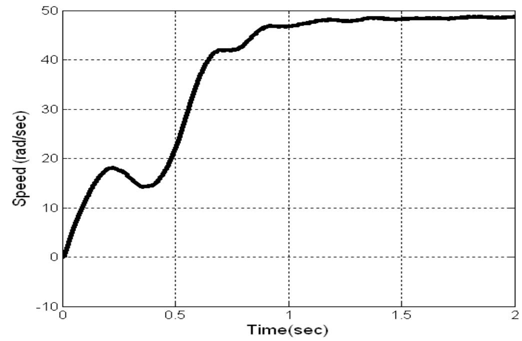

Fig. 9: Rotor speed in Classical DTC

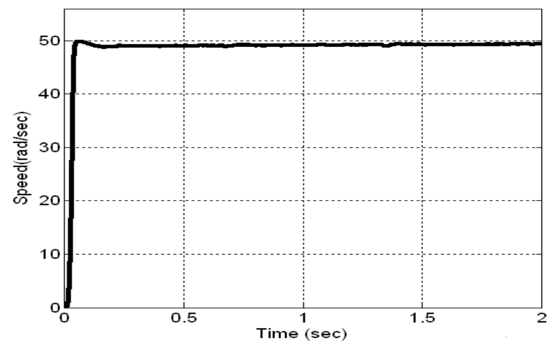

Fig. 10: Rotor speed in SVM-DTC

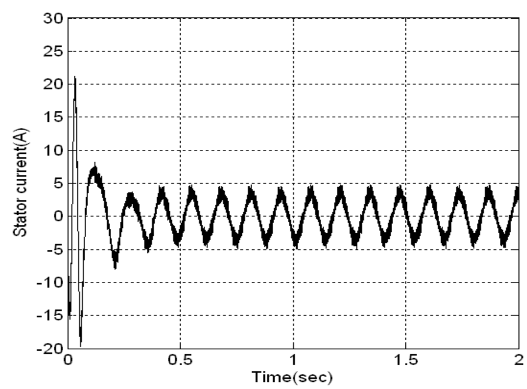

Fig. 11: Stator current in Classical DTC

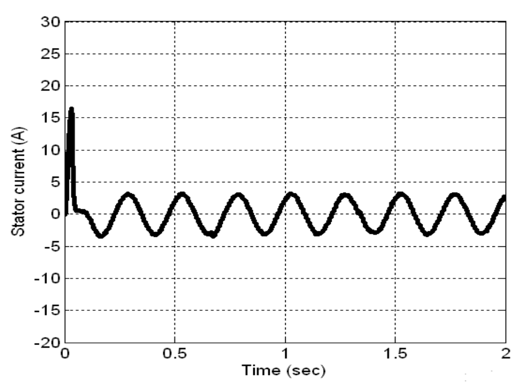

Fig. 12: Stator current in SVM-DTC

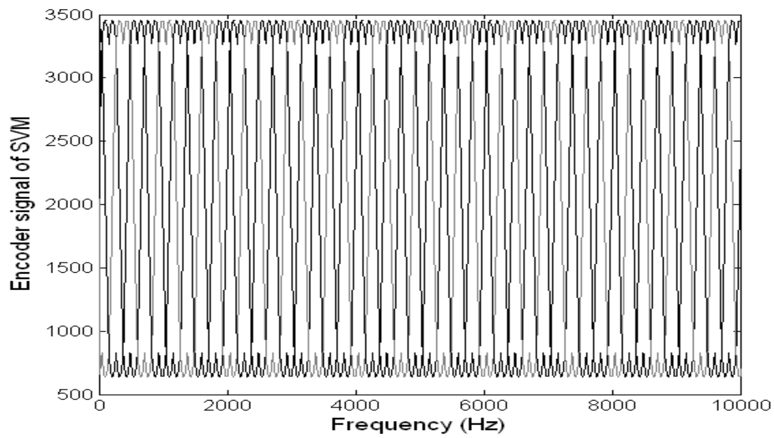

Fig. 13: Output signals of SVM

model with classical DTC is studied too. The result of both classical DTC and proposed SVM-DTC in term of speed, torque and flux and current are shown below.

From Fig. 5 and 6, it can be noted that the ripple of torque in proposed method at low speed (50 rad/sec) is reduced with fast response. .In contrast, the torque ripple cannot be neglected in classical DTC.

Stator flux in classical DTC as shown in Fig. 7 maintain circular orbit but with high ripple while the ripple of flux in SVM-DTC is reduced as shown in Fig. 8.

In addition , it can be seen that the rotor speed in classical DTC reach the steady state value within 900 ms as shown in Fig. 9 but in proposed SVM- DTC, the rotor speed reach steady state within 60 ms as shown in Fig. 10.

The stator current of traditional DTC suffer from distortion which cause increasing harmonics and degrade the performance system comparing with proposed SVM-DTC as shown below (Fig. 11 and 12).

Finally,The output signals of space vector modulation are shown in Fig. 13 and these signals show the effectiveness of the proposed controller, also demonistrate high quality for this algorithm to runing the induction motor practically especially under heavy load at low speed.

CONCLUSION

This proposed method describes the performance of Direct Torque Control (DTC) based on space vector modulation, amplitude voltage and stator flux angle. In this system, hysteresis controller is substituted with PI torque controller and PI flux controller while switching table is replaced by SVM in order to improve the performance of this system especially at low speed, SVM is based on amplitude voltage and stator flux angle. The stator flux angle is controlled by PI torque controller and stator angular frequency and this gives a high accuracy for the value of the angle due to presence of PI torque controller. The amplitude voltage is controlled by PI torque and PI flux controller. This proposed method shows a reduction ability of flux and torque ripple with constant switching frequency and fast response of speed .This control technique can be done practically by using Digital Signal Processing (DSP) board.

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