

Performance Evaluation of Constant Frequency Torque Controller-Based and SVM-Based of Direct Torque Control of Induction Motor Drives

M. Zarafi, N. R. N. Idris, Z. H. Ismail, S. Aizam and H. Rohaiza

Abstract—Direct torque control is a control technique used in AC drive system to obtain high performance torque control. The conventional DTC drive contains a pair of hysteresis comparators, a flux and torque estimator and voltage look-up table. The torque and flux are controlled simultaneously by applying suitable voltage vectors, and limiting these quantities within their hysteresis band. At the same time, de-coupled control of torque and flux were achieved. However, the DTC drives utilizing hysteresis comparators suffer from high torque ripple and variable switching frequency. The most common solution to this problem is to use the space vector based which depends on the reference torque and flux. The reference voltage vector is then realized using a voltage space vector modulator (SVM). Nevertheless, by applying this method, the basic structure of DTC is lost and needs for high performance of processor. On the other hand, constant frequency torque controller also has managed to solve the problem. The proposed controller has retained the basic structure of DTC drive as in hysteresis-based. This paper present the comparison and evaluation of the performances of those techniques of DTC drive that applied to induction machine through simulation using MATLAB/SIMULINK. The evaluation was made based on the drive performances, which include dynamic torque, feasibility, and the complexity of the system. The results obtained showed that the constant frequency torque controller-based gives better performance in terms of dynamic torque and at the same time retain the simple structure of DTC drive system.

Keywords: induction motor, space vector modulation (SVM), constant switching, direct torque control (DTC).

I. INTRODUCTION

Direct torque control (DTC) of induction motor drives becomes popular and widely used in industrial applications due to a fast and good dynamic torque response as well as

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provides a simple control structure. Since it was introduced in the middle of 1980's [1], [2] many researchers have been working in this area and several modifications and improvements have been made in order to overcome the two major disadvantages of the hysteresis-based of DTC scheme, namely the high torque ripple and variable switching frequency of the inverter. Previous proposed techniques to overcome these problems include the use of variable hysteresis band, controlled duty cycle technique and use of space vector modulation (DTC-SVM) based. All these techniques have managed to improve the performance of DTC, in the expense of losing the simple structure of DTC. In [3]-[5], a simple approach to solve the problems and at the same time retaining the simple structure of DTC was introduced. In this approach, a constant frequency torque controller was used to replace the hysteresis torque controller.

For DTC-SVM based, in order to reduce the torque ripple and to fix the switching frequency, the control system should be able to generate a desired voltage vector by means of space vector modulator. Therefore, using this technique it is require for more complex control structure and present motor parameters dependence. The increased number of voltage vectors allows the definition of more accurate switching tables in which the selection of the voltage vectors is operated according to the rotor speed, the flux error and the torque error. Due to all of these requirements and to obtain a small torque ripple, the DTC-SVM drive is requiring for fast processor.

In the case of constant frequency torque controller based, the method used in obtaining a constant switching frequency and reducing the torque ripple is much simple. It is accomplished by introducing a new torque controller to replace the torque hysteresis-based controller. This means that the simple structure of DTC as initially proposed by I. Takahashi is retained.

This paper investigates the performance of the direct torque control of space vector modulation-based and constant frequency torque controller-based. The evaluation is made on the performance of dynamic torque response, torque ripple and the structure of both schemes. The rest of

the paper is organized as follows. Section II presents the basic concepts of DTC drives. Section III describes the principles of SVM-based and constant frequency torque controller-based of DTC. Section IV discusses the simulation results of both schemes. Finally, conclusions are given in Section V.

II. BASIC CONCEPTS OF DTC

AC motors are the most common motors used in industrial motion control system, as well as in main powered home appliances. Simple and rugged design, low cost, low maintenance and direct connection to an AC source are the main advantages of AC induction motors. Due to the advantages, it always has a competitor in the DC-motor or universal-motor. At present, induction motor drives are dominating the world market.

Since two decades ago, DTC of induction motor drives based on vector control have become popular and widely used due to its advantages. The first DTC scheme was introduced in 1980's as an alternative to field-oriented control (FOC) scheme. The configuration of DTC is very simple and gives fast and good dynamic torque response. If compared to the field-oriented control technique, in DTC scheme, there is no need for co-ordinate transformation, pulse-width modulator, and speed sensor. Nowadays, many applications especially in industrial have switched to this control technique in order to get better performances of the induction motor used.

In order to analyze the DTC in terms of its switching frequency and torque ripples, the induction motor equations written in general reference frame are used:

$$\bar{v}_s^g = R_s \bar{i}_s^g + \frac{d\bar{\psi}_s^g}{dt} + j\omega_g \bar{\psi}_s^g \quad (1)$$

$$0 = R_r \bar{i}_r^g + \frac{d\bar{\psi}_r^g}{dt} + j(\omega_g - \omega_r) \bar{\psi}_r^g \quad (2)$$

Where

$\bar{\psi}_s^g$ and $\bar{\psi}_r^g$ are the stator and rotor flux leakages respectively and given by

$$\bar{\psi}_s^g = L_s \bar{i}_s^g + L_m \bar{i}_r^g \quad (3)$$

$$\bar{\psi}_r^g = L_r \bar{i}_r^g + L_m \bar{i}_s^g \quad (4)$$

In the above equations, \bar{v}_s^g , \bar{i}_s^g , and \bar{i}_r^g are the stator voltage, stator current and rotor current space vectors respectively, whereas L_s , L_r , and L_m are the stator self inductance, rotor self inductance and mutual self inductance, respectively. All of the equation are referred to the rotating general reference frame which represented by superscript "g". ω_g and ω_r are the speed of the general reference frame and rotor respectively.

In a symmetrical three phase induction motor, the instantaneous electromagnetic torque is proportional to the

cross vectorial product of the stator flux linkage space vector and the stator current space vector,

$$t_e = \frac{3}{2} p \bar{\psi}_s \times \bar{i}_s \quad (5)$$

Where $\bar{\psi}_s$ and \bar{i}_s is the vector of stator flux linkage and stator current respectively, while p is the number of pole-pairs. Equation (5) also can be written in the following form:

$$t_e = \frac{3}{2} P |\bar{\psi}_s| |\bar{i}_s| \sin(\alpha_s - \rho_s) \quad (6)$$

Where α_s is the stator current angle and ρ_s is the stator flux angle space vector in the horizontal axis of the stationary frame as shown in 'figure 1'.

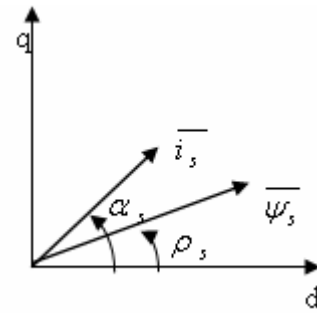


Figure 1. Stator flux leakage and stator current space vector

By manipulating equations (3) and (4), the electromagnetic torque in the stationary reference frame in equation (6) becomes:

$$t_e = \frac{3}{2} P \frac{L_m}{L_s L_r} \bar{\psi}_s \times \bar{\psi}_r \quad (7)$$

$$= \frac{3}{2} P \frac{L_m}{L_s L_r} \psi_s \psi_r \sin(\rho_s - \rho_r) \quad (8)$$

$$= \frac{3}{2} P \frac{L_m}{L_s L_r} \psi_s \psi_r \sin \delta_{sr} \quad (9)$$

where ρ_r is the angle of the rotor flux and $\delta_{sr} = \rho_s - \rho_r$ is the angle between the stator and rotor flux space vector with respect to the real axis of the stationary reference frame.

In DTC, rapid changes of the torque can be obtained by rotating the stator flux in the forward direction or by rotating in the reverse direction or by stopping it according to the demanded torque [6]. In other words, the direct torque control can be achieved by quickly changing the position of the stator flux space vector (change in δ_{sr}). For simplicity, it is assumed that the stator resistance is small and can be neglected, thus the stator voltage equation can be expressed as below,

$$\frac{d\bar{\psi}_s}{dt} = \bar{v}_s \quad (10)$$

or

$$\Delta\bar{\psi}_s = \bar{v}_s \Delta t \quad (11)$$

If the induction motor is supplied by three phase voltage source inverter (VSI), it consists of eight possible voltage switching space vectors (v_1 v_8) by means of six active switching vectors (v_1 to v_6) and the rest is zero switching vectors (v_7 and v_8). Figure 2 shows the corresponding of eight switching vectors and the voltage space vector, hence the dc link voltage V_{dc} can be expressed as follows:

$$\bar{v}_s(t) = \frac{2}{3} V_{dc} (v_{sA}(t) + a v_{sB}(t) + a^2 v_{sC}(t)) \quad (12)$$

where

$$a = e^{j2\pi/3}$$

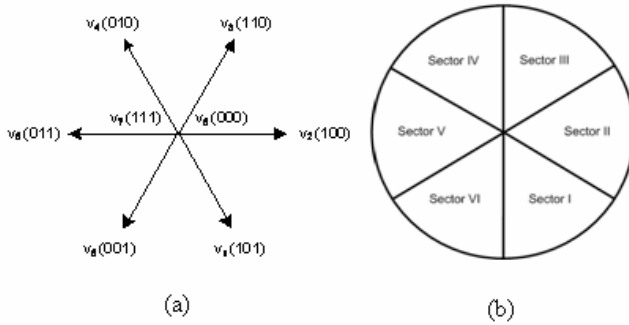


Figure 2. (a) Voltage vectors of three-phase VSI; (b) Six sectors of stator flux plane

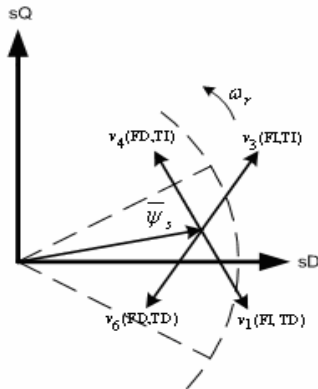


Figure 3. Position of stator flux space vector (FI: flux increase; FD: flux decrease; TI: torque increase; TD: torque decrease)

From equation (11), the stator flux vector can be moved with small change in time. Hence, the stator flux can be controlled and forced to follow the reference flux given by selecting the appropriate switching of voltage vectors. In order to select the appropriate voltage vectors of the inverter, (either to increase or reduce stator flux and either to increase torque or to reduce torque) it is depends on the position of stator flux vector on the stator flux plane as shown in ‘figure 2(b)’. Let the stator flux is in sector II and

rotates in counter-clockwise direction as illustrated in ‘figure 3’. If an increase in the electromagnetic torque is required, the stator flux can be increased and decreased by selecting voltage vector v_3 and v_4 respectively. Whereas, if decrease torque is required (stator flux moving in clockwise direction), switching vector v_1 and v_6 will cause the stator flux to increase and decrease respectively. Stopping the rotation of the stator flux corresponds to the case when the electromagnetic torque does not have to be changed. This condition is defined when the reference value of the torque is equal to its actual value and to stop the rotation, zero switching vector (v_7 or v_8) is applied.

According to the stator flux plane, a set of switching voltage vectors or rules of which voltage vector should be chosen in a particular sector can be constructed as illustrated in ‘table 1’.

Table 1. Voltage vectors selection table

Counter clockwise		Sec I	Sec II	Sec III	Sec IV	Sec V	Sec VI
Inc Flux	Inc Torque	100	110	010	011	001	101
	Dec Torque	000	111	000	111	000	111
Dec Flux	Inc Torque	110	010	011	001	101	100
	Dec Torque	111	000	111	000	111	000
Clockwise		Sec I	Sec II	Sec III	Sec IV	Sec V	Sec VI
Inc Flux	Inc Torque	001	101	100	110	010	011
	Dec Torque	000	111	000	111	000	111
Dec Flux	Inc Torque	011	001	101	100	110	010
	Dec Torque	111	000	111	000	111	000

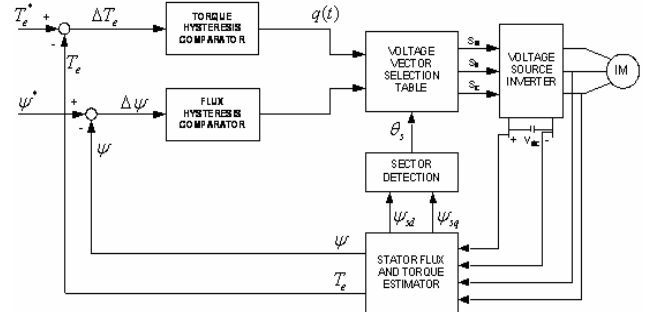


Figure 4. Basic configuration of DTC (hysteresis-based)

The basic system configuration of DTC scheme is depicted in ‘figure 4’. The reference values of torque and flux are compared with the measured value of torque and stator flux respectively, which are calculated in the estimator block. The error values from the comparison process are fed into three-level and two-level hysteresis comparator respectively. According to the hysteresis comparators, it is used to restrict the flux and torque errors within the hysteresis band in order to obtain a good torque response. The restricted values in digital signal are used to select the voltage vectors of the inverter listed in Table 1. It is also depends on the position of stator flux on its stator flux plane as illustrated in ‘figure 2(b)’.

III. PRINCIPLES OF DTC-SVM BASED AND CONSTANT FREQUENCY TORQUE CONTROLLER BASED

A. DTC-SVM Based

There are various types of direct torque control-space vector modulation schemes that have been proposed by many researchers. Each scheme will perform the different control technique but its aims are still similar which is to attain the constant switching frequency and to reduce the torque ripple. The differences between various DTC-SVM are on how the reference voltage is generated – the reference voltage is then implemented using space vector modulator. Space vector modulation is used to define the inverter switching state or voltage vector positions different from six standard positions.

In this paper, the focus is only on the DTC-SVM scheme with closed-loop torque control. For this technique, it is based on load angle control strategy and significantly overcomes the most important drawbacks of conventional DTC hysteresis-based [7], [8]. A single space vector that represent the usual space vector transformation apply to a three-phase voltage system is define as

$$v_s = \frac{3}{2}(v_a + av_b + a^2v_c) \quad (13)$$

where $a = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$ and it is possible to obtain a simple equation set that describe the AC machine dynamic behavior in a stator fixed coordinate system as in equation (1) - (4). As stated in equation (9), it is representing the basic relation between torque and machine fluxes. Based on equation (7), it is possible to achieve machine speed and torque control directly by actuating over the load angle.

Due to slow rotor flux dynamics, the easiest way to change the load angle is to force a change in the stator flux by application of the appropriate stator voltage vector, v_s [9]. By assuming the voltage drop on the stator resistance in equation (1) is small which can be neglected, the stator flux vector is the time integral of the stator voltage vector.

In DTC-SVM with closed-loop torque control, the aim is to select the exact stator voltage vector, v_s that change ψ_s to meet the load angle reference, and the desired torque while keeping the flux amplitude constant. A space vector modulation algorithm is used to apply the required stator voltage vector. It is expected that torque ripple is almost eliminated. By additional of proportional-integral (PI) regulator, a simple flux calculation block is applied and at the same time departs from the rotating coordinate transformation. This strategy is straightforward by using of equation (7) [10]. The block diagram of DTC-SVM based is illustrated in ‘figure 5’. Even this technique has managed to overcome the two main drawback of conventional DTC, it is leads to increase the complexity of DTC configuration and needs for fast processor to be implemented in digital system.

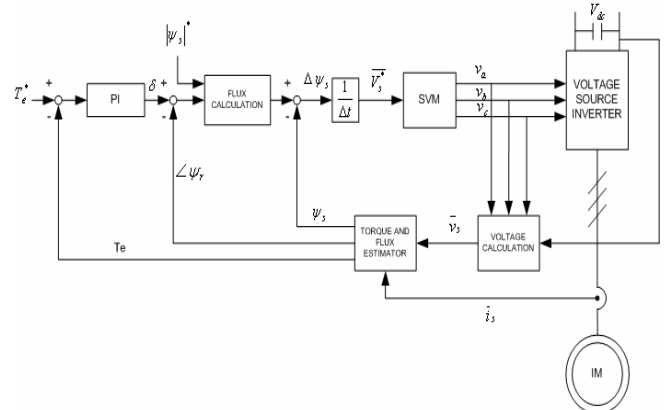


Figure 5. Block diagram of DTC-SVM with torque controller

B. Constant Frequency Torque Controller-Based of DTC

A constant frequency torque controller for DTC of an induction motor drive has been proposed as in reference [3]-[5] to overcome the same problem described previously. The controller is capable of producing constant switching frequency in the drive operating condition and at the same time reduced for high torque ripples. In advance, the implementation of the controller is simple and the basic drive control structure is retained as in hysteresis DTC drive. A simple structure of torque controller has been introduced to replace the conventional three-level torque hysteresis comparator that used in conventional DTC scheme. A constant switching frequency is obtained by comparing a fixed frequency of triangular carrier signals with the compensated torque error signals from the PI controller. ‘Figure 6’ shows the structure of the constant frequency torque controller used in this strategy.

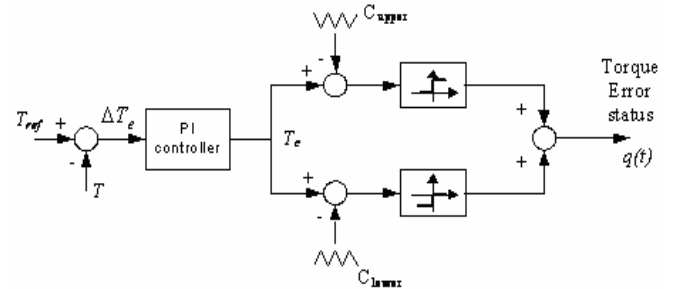


Figure 6. The structure of the constant frequency torque controller

The controller consists of two triangular waveform generators, two comparators and a PI controller as shown in ‘figure 6’. The two triangular waveforms C_{upper} and C_{lower} are 180° out of phase from each other. The working principle of the controller is similar to the three-level torque hysteresis comparator as in conventional DTC [1]. The output of the controller can be either of three level which is 1, 0 or -1 . The designated value of the instantaneous output of the controller and the averaged triangular period is given by equation (14) and (15) respectively. The overall configuration of DTC utilizing a constant frequency torque controller is shown in ‘figure 7’.

$$q(t) = \begin{cases} 1 & ; \text{for } T_c \geq C_{\text{upper}} \\ 0 & ; \text{for } C_{\text{lower}} < T_c < C_{\text{upper}} \\ -1 & ; \text{for } T_c \leq C_{\text{lower}} \end{cases} \quad (14)$$

$$d(t) = \frac{1}{T_{\text{tri}}} \int_t^{t+T_{\text{tri}}} q(t) dt \quad (15)$$

The dynamics of the motor is modeled by the following

$$J \frac{d\omega_m}{dt} = J \frac{2}{p} \frac{d\omega_r}{dt} = T_e - T_{\text{load}} \quad (16)$$

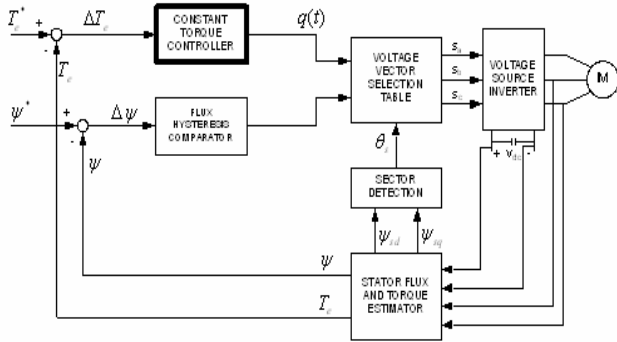


Figure 7. The configuration of constant frequency torque controller in DTC drive

Using (1) – (6) and, (16) in the stationary reference frame, the positive and negative torque slopes are given by

$$\frac{dT_e^+}{dt} = -T_e \left(\frac{1}{\sigma\tau_s} + \frac{1}{\sigma\tau_r} \right) + \frac{3}{2} \frac{p}{2} \frac{L_m}{\sigma L_s L_r} (\bar{v}_s - j\omega_r \bar{\psi}_s) \cdot j\psi_r \quad (17)$$

$$\frac{dT_e^-}{dt} = -T_e \left(\frac{1}{\sigma\tau_s} + \frac{1}{\sigma\tau_r} \right) - \frac{3}{2} \frac{p}{2} \frac{L_m}{\sigma L_s L_r} j\omega_r \bar{\psi}_s \cdot j\psi_r \quad (18)$$

where σ is the total flux leakage factor, and τ_s and τ_r are the stator and rotor time constant respectively.

These are simplified by assuming that the stator and rotor fluxes are constant and the q components of the selected voltage vectors are zero, which is the voltage vectors are tangential to the circular stator flux locus. The average and simplified torque loop equation is written as

$$\frac{dT_e}{dt} = -A_t T_e + B_t v_s^{vs} d + K_t (\omega_{\text{slip}}) \quad (19)$$

Where

$$A_t = \frac{1}{\sigma\tau_{sr}} \quad B_t = \frac{3p}{4} \frac{L_m}{\sigma L_s L_r} \psi_s \quad K_t = \frac{3p}{4} \frac{L_m}{\sigma L_s L_r} (\psi_s \psi_r^{vs})$$

Finally, the torque equation in s-domain can be written as

$$T_e(s) = \frac{B_t v_s^{vs} d(s) + K_t \omega_{\text{slip}}(s)}{s + A_t} \quad (20)$$

According to (20) and linearized it, the torque loop as shown in 'figure 8' can be constructed.

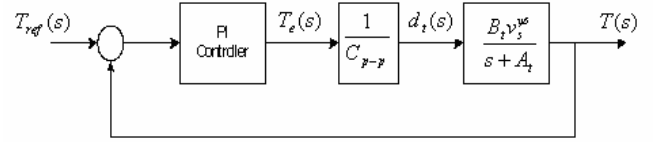


Figure 8 Linearized torque loop.

IV. SIMULATION RESULTS

The simulation of DTC-SVM based and constant frequency torque controller based of DTC induction motor drive was performed using MATLAB/SIMULINK simulation package. The parameters of induction machine as tabulated in 'table 1' were used in the simulations.

Table 2: Induction machine parameters.

Stator resistance	5.5 Ω ,	Moment of inertia	0.01 kgm^2
Rotor resistance	4.51 Ω	Number of poles	4
Stator self inductance	306.5 mH	Rated speed	1410 rpm
Rotor self inductance	306.5 mH	Vdc	654 V
Mutual inductance	291.9 mH	Load torque	1 Nm

For constant frequency torque controller based, the frequency of upper and lower triangular waveforms employed for constant torque controller is set at 20 kHz with a peak-to-peak of 100 units. While the gain K_p and K_i of PI controller are set to 57 and 3630 respectively [5]. The magnitude of stator flux reference is set at its rated value which is 1.2 Wb for both schemes and the stator flux is restricted within its hysteresis band of 0.05 Wb.

The results from the simulation show that the stator flux locus trajectories is circular when the voltage vectors switched between two active and zero vectors as depicted in 'figure 9'. 'Figure 10' shows the torque response of both scheme with ± 4 Nm square-wave torque reference. Both scheme have manage in reducing the torque ripples as discuss in [3]-[5] and [7]-[10], the simulation results of torque ripple demonstrate that DTC-SVM based and constant frequency torque controller based have almost same performance ($\Delta T \approx 0.15$ Nm). However, in terms of dynamic torque response, DTC-SVM based has slow dynamic compared to the constant frequency torque controller based. 'Figure 11' shows the constant switching of both DTC schemes obtained from the simulation. For DTC-SVM, the switching signal is determined by mathematical equation whereas for constant frequency torque controller based is determined by comparing the triangular waveform with the output of PI controller.

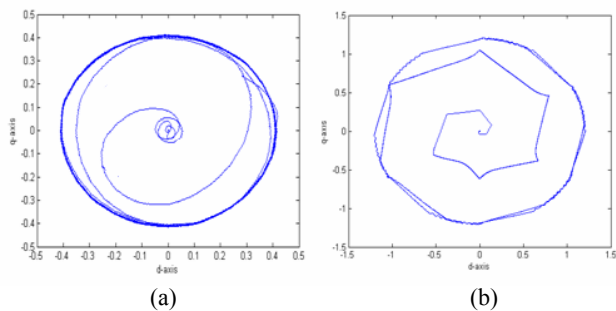


Figure 9 Flux locus. (a) DTC-SVM based, (b) Constant frequency torque controller based ($\Delta\psi = 0.03\text{Wb}$).

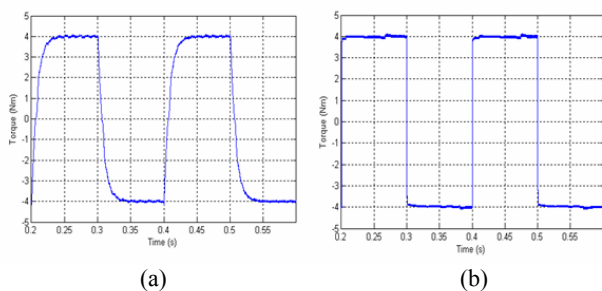


Figure 10 Torque response. (a) DTC-SVM based, (b) Constant frequency torque controller based.

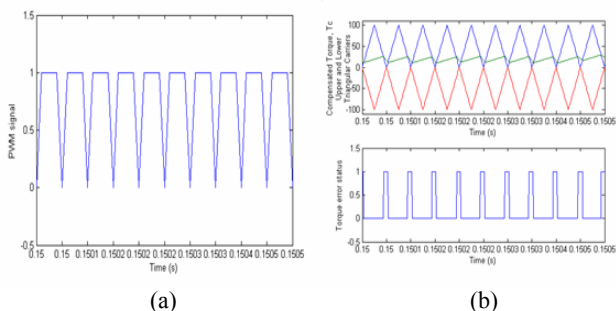


Figure 11. Switching signal. (a) DTC-SVM based, (b) Constant frequency torque controller based

V. CONCLUSION

This paper has presented two different approaches of DTC drives in order to fix the switching frequency and reduce high torque ripple addressed in conventional DTC scheme (hysteresis-based). From the simulation results obtained, the torque ripple of DTC-SVM with closed-loop torque control is much less than constant frequency torque controller-based. However, the dynamic torque response during transient condition is slower than constant frequency torque controller-based to achieve the steady-state condition. In the case of constant frequency torque controller-based, the structure of DTC drive is simple and retain as conventional DTC (hysteresis-based) but not for DTC-SVM. Even though, both scheme has manage to fix the switching frequency.

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