

High Performance Direct Torque Controlled Induction Motor Drive For Adjustable Speed Drive Applications

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Abstract

Among all control methods for induction motor drives, Direct Torque Control (DTC) seems to be particularly interesting being independent of machine rotor parameters and requiring no speed or position sensors. The DTC scheme is characterized by the absence of PI regulators, coordinate transformations, current regulators and PWM signals generators. In spite of its simplicity, DTC allows a good torque control in steady state and transient operating conditions to be obtained. This paper is aimed to analyze DTC principles, the strategies and the problems related to its implementation and the possible improvements using Space Vector Pulse Width Modulation (SVPWM). In SVPWM for each sampling period the switching instants of different space vectors are determined to reduce torque ripple. The time durations of two adjacent voltage space vectors and the corresponding zero voltage space vectors are determined in this method depending on maximum and average switching frequency, allowable for the switching devices in the three phase inverter. Simulation studies have been carried out for different operating conditions of the drive system. The results have been presented and compared with those of the conventional method.

1. Introduction

In its basic configuration, a conventional direct torque control (DTC) system consists of a pair of hysteresis comparators, torque and flux estimator, Voltage vector selector, and a Voltage Source inverter (VSI). Despite its simplicity, DTC systems offer Comparable or even better torque performance to that of DC machines. The torque and stator flux are regulated within their hysteresis bands independently by applying appropriate voltage vectors to the VSI. The voltage vectors are selected based on the outputs of

torque and stator flux hysteresis comparators, as well as the stator flux orientation.

It is shown in [1, 2] that the rate of change of torque and stator flux, and hence the time taken for the flux and torque to touch their upper and lower bands, depend on the operating condition (i.e., rotor speed, stator and rotor fluxes, and DC link voltage). Since the device switching frequency of the VSI is directly related to the switching of the torque and stator flux hysteresis comparators, it follows that the device switching frequency depends on the operating conditions. The variable switching frequency, although may result in less irritating noise emissions, produces a wide band of harmonic spectra and is thus more likely to induce mechanical resonance. This, in turn, may result in higher noise emission. At low speed, the positive torque slope is large, which can cause torque overshoot, hence increasing the torque ripple. This is undesirable, especially for applications that require precise torque control.

Since it is existed greater torque ripple, poorer performance of low speed region, and inconstant switch frequency, two of the major areas of concern are on torque ripple reduction and constant switching frequency. Recent advance in DTC systems have contributed significantly to research new control method in the field of modern AC drive. It includes the use of predictive control scheme [3], space vector modulation (SVM) technique [4,5], and fuzzy logic control [6]. In [3], a concept of forward voltage vector was proposed, and the voltage vector of next control cycle was calculated by using the torque error and the flux error. This method can reduce effectively torque and current ripple, resulted in a constant switching frequency, but it requires solving a quadratic equation to obtain the desired voltage vectors. All of these methods have managed to fix the switching frequency and to some extent reduce the torque ripple; however, they require additional calculation and high-speed microprocessor, which outweigh the simple control structure of the DTC.

In recent years, the space vector pulse width modulation (SVPWM) technique demonstrated some improvement for both the output crest voltage and the harmonic copper loss. The maximum output voltage based on the space vector theory is 1.15 times as large as the conventional sinusoidal modulation. It makes it possible to feed the motor with a higher voltage than the easier sub-oscillation modulation method. This modulator enables higher torque at high speeds, and a higher efficiency.

This paper proposes a novel control method of DTC based on SVPWM to give a constant torque switching frequency and reduces the torque ripple. This method is used in a variable-speed asynchronous motor drive. In this control scheme, a d-q coordinate's reference frame locked to the stator flux space vector is used to achieve decoupling between the motor flux and torque. They can be thus independently controlled by stator d-axis voltage and q-axis voltage. Section two of the paper presents motor torque-stator voltage relationship of the induction motor. Section three presents the principle of conventional DTC. Section four presents proposed SVPWM DTC technique and final section presents the simulation results, and makes some discussion on the simulation results. Section six draws the conclusions.

2. Motor torque-stator voltage relationship

In order to deeply analyze the basic DTC principles it is possible to determine the analytical relationships between the applied voltage vector and the corresponding torque and flux variations. For this purpose reference is made to the induction motor equations in a stationary reference frame, written in the state-space form

$$\begin{bmatrix} \frac{d\phi_s}{dt} \\ \frac{d\phi_r^s}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{\sigma L_s} & \frac{R_s M}{\sigma L_s L_r} \\ \frac{R_r M}{\sigma L_s L_r} & j\omega_k - \frac{R_r}{\sigma L_r} \end{bmatrix} \begin{bmatrix} \phi_s \\ \phi_r^s \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} v_s \quad (1)$$

Equation (1) can be discretized by means of the small signal analysis. For small values of T_c , the stator and rotor flux space vectors can be expressed as

$$\phi_{sk+1} = \phi_{sk} \left(1 - \frac{R_s}{\sigma L_s} T_c \right) + \phi_{rk}^s \frac{R_s M}{\sigma L_s L_r} T_c + v_{sk} T_c \quad (2)$$

$$\phi_{rk+1}^s = \phi_{rk}^s \left(1 + \left(j\omega_k - \frac{R_r}{\sigma L_r} \right) T_c \right) + \phi_{sk} \frac{r_r M}{\sigma L_s L_r} T_c \quad (3)$$

Equations (2) and (3) are the discrete-time equations of an IM. Note that in (11) the stator voltage v_{sk} does not appear explicitly, meaning that v_{sk} acts on the rotor through the stator flux. Furthermore, the electromagnetic torque at T_{k+1} is given by

$$T_{k+1} = \frac{3}{2} p \frac{M}{\sigma L_s L_r} \left(\delta_{sk+1} \cdot j \delta_{rk+1}^s \right) \quad (4)$$

Substituting (2) and (3) into (4) and neglecting the terms proportional to the square of T_c , the torque at T_{k+1} can be expressed as

$$T_{k+1} = T_k + \Delta T_{k1} + \Delta T_{k2} \quad (5)$$

$$\Delta T_{k1} = -T_k \left(\frac{R_s}{L_s} + \frac{R_r}{L_r} \right) \frac{T_c}{\sigma}$$

$$\Delta T_{k2} = p \frac{M}{\sigma L_s L_r} \left[(v_{sk} - j\omega_k \phi_{sk}) \cdot j \phi_{rk}^s \right] T_c \quad (6)$$

The term ΔT_{k1} has opposite sign of T_k and then reduces the torque; its value is proportional to the stator and rotor resistances and to the torque at T_k and is independent of v_{sk} and the motor speed. The term ΔT_{k2} is due to the stator voltage and depends on the operating conditions. A graphical representation of $\Delta T_k = \Delta T_{k1} + \Delta T_{k2}$, useful to visualize the effects of the applied voltage vector on the motor torque, is drawn in Figure 1 for zero motor speed and in Figure 2 for the rated motor speed.

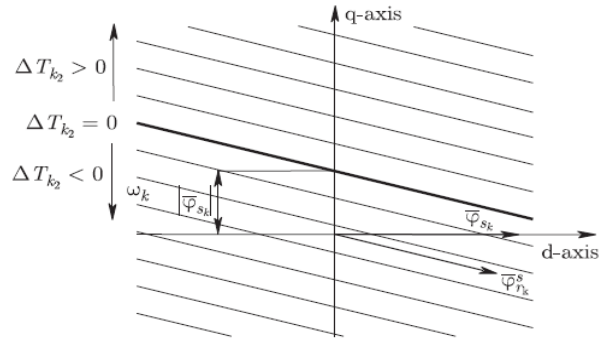


Figure 1. Diagram of the torque variation ΔT_{k2}

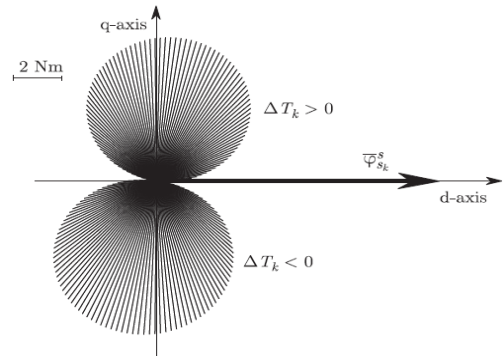


Figure 2. Torque variations at zero speed (rated torque)

These figures report the torque variation ΔT_k produced by a stator voltage space vector of constant amplitude and for several values of its displacement with respect to the stator flux. The segments have a

length proportional to the torque variation and the same direction as the stator voltage space vector. The ones in the upper part of the figures represent positive variations of the torque while those in the lower part represent negative variations. The advantages of this solution are a better torque response over the whole speed range and a reduction in the torque ripple.

3. Proposed SVPWM-DTC technique

In conventional DTC systems, the torque error and flux error are used to generate directly next switching condition of the VSI. However, the new method is that use two errors to produce stator reference voltage vectors, then they are modulated by means of the SVPWM technology. At last, a constant switching frequency signal is exported to the VSI. The new DTC variable-speed system control principles will be introduced orderly as follows.

3.1. Produce Reference Voltage Vectors

The flux regulator determines the voltage vector, which has to be applied to the motor in order to obtain at any instant, a stator flux vector equal to its reference value (λ_s^*). This can be properly obtained by using a regulator in which the input variable is difference between the reference and the estimated flux vectors

$$\Delta\lambda_s = \lambda_s^* - \lambda_s \quad (8)$$

The flux regulator equation can be expressed as follows:

$$\bar{V}_s^* = R_s \bar{i}_s + j\omega \bar{\lambda}_s + K_p \Delta\lambda_s \quad (9)$$

This equation shows that the flux regulator behaves as a proportional controller, with some additional terms compensating the stator back electromotive force and the stator resistant voltage drop in (6) K_p represents the gain of the regulator. The angular frequency ω needed in (9) is obtained by the following equation:

$$\omega = \frac{de^{j\theta}}{dt} \cdot je^{j\theta} \quad (10)$$

The angular frequency is insensitive to disturbances and noise that usually affect the stator flux and stator currents, owing to the filtering action applied to the rotor flux. When this action is not adequate an additional low-pass filter can be applied to (10).

3.2. Modulate Voltage Reference Vector

The SVPWM technique refers to a special switching scheme of the six power transistors of a 3-phase power inverter. It generates minimum harmonic distortion to the currents in the windings of a 3-phase AC motor. It

also provides more efficient use of supply voltage in comparison with the sinusoidal modulation method. The SVPWM technique uses eight sorts of different switch modes of inverter to control the stator flux to approach the reference flux circle, and attains the higher control performance. Eight sorts of switch modes are corresponding respectively to eight space voltage vectors that contain six nonzero vectors and two zero vectors.

Applying the phase voltages corresponding to the eight combinations onto the $d-q$ plane by performing a $d-q$ transformation (which is equivalent to an orthogonal projection of the 3-vectors (a b c) onto the two dimensional plane perpendicular to the vector (1,1,1), the $d-q$ plane), results in six nonzero vectors and two zero vectors

The six nonzero vectors form the axes of a hexagonal. The two zero vectors are at the origin. The eight vectors are called the basic space vectors and are denoted by V_1 (100), V_2 (110), V_3 (010), V_4 (011), V_5 (001), V_6 (101) V_0 (000), and V_7 (111). E.g. V_1 (100), "a=1" denotes the upper leg of a phase is switched on, "bc=00" mean the lower legs of b and c phases is on. Fig. 4 shows the basic switching vectors and sectors vectors. The six nonzero vectors divide equally the $d-q$ plane into six sectors. The sectors are numbered by S1& the angle between two adjacent vectors is 60 degrees

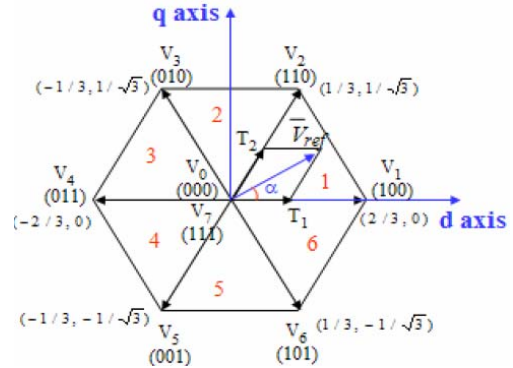


Figure 4. Basic switching vectors and sectors

Figure 5 shows the process of compounding V_{ref} by V_1 and V_2 . In order to make the stator flux approaching the reference flux circle, the following equation is given by average equivalent principle.

$$T_Z \bar{V}_{ref} = T_1 \bar{V}_1 + T_2 \bar{V}_2 \quad (11)$$

$$T_Z = T_1 + T_2 + T_0 \quad (12)$$

Where T_Z is the PWM carrier period, T_1 and T_2 is the time duration of V_1 and V_2 , respectively, and T_0 is zero vector time duration. The inclusion of zero basic vectors doesn't affect the vector sum \bar{V}_{ref} , only helps to balance the turn on and off periods of the transistors, and thus their power dissipation.

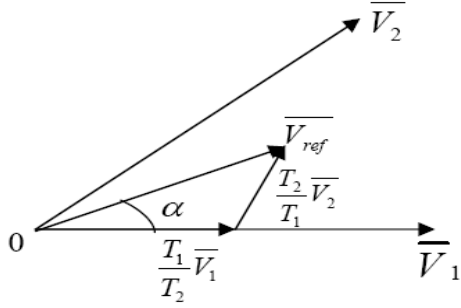


Figure 5. Reference vector as a combination of V_1 & V_2

Fig.6 shows the Space Vector PWM switching patterns in sector S_1 . The time duration of each nonzero vector is divided equally into two parts, the time duration of zero vectors is distribute equally to V_0 and V_7 , and thus the switching sequence of space vector is V_0 - V_1 - V_2 - V_7 - V_7 - V_2 - V_1 - V_0 in the PWM period. This sequence can ensure that is only one transistor switches when the switching pattern switches, hence can reduce the loss of switching devices and the harmonic component of the output current of the VSI. (Where S_1, S_3, S_5 , are upper transistors , S_4, S_6, S_2 lower transistor of the inverter)

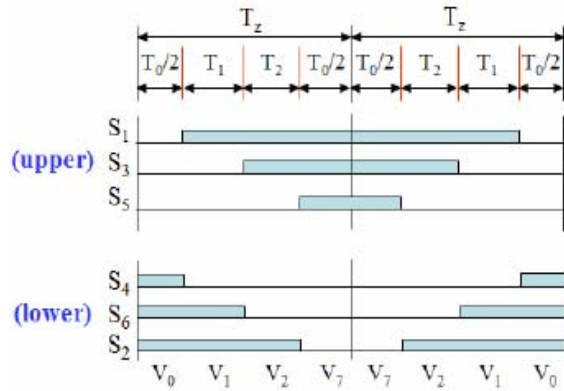


Figure 6. Space Vector PWM switching pattern in sector

The switching time duration T_1 , T_2 and T_0 at any sector is given by

$$T_1 = \frac{\sqrt{3} \cdot T_z \cdot |V_{ref}|}{V_{dc}} \left(\sin \frac{n}{3} \pi \cos \alpha - \cos \frac{n}{3} \pi \sin \alpha \right) \quad (13)$$

$$T_2 = \frac{\sqrt{3} \cdot T_z \cdot |V_{ref}|}{V_{dc}} \left(-\cos \alpha \cdot \sin \frac{n-1}{3} \pi + \cos \frac{n-1}{3} \pi \cdot \sin \alpha \right) \quad (14)$$

$$T_0 = T_z - T_1 + T_2 \quad (\text{Where } n=1 \text{ to } 6 \text{ i.e sector } 1 \text{ to } 6)$$

The 3-phase PWM control signal is exported Pass through the SVPWM modulation, its pulse width rely on the value of the T_1 , T_2 and T_0 .

3.3. Structure of control system

In the DTC variable-speed control system of Figure 7, the induction motor is fed by a VSI, which operates as a three-phase sinusoidal voltage source. By Clark transformation the measured three-phase stator voltages V_{abc} and stator currents i_{abc} are converted into two-phase voltages V_{sd} V_{sq} and currents i_{sd} , i_{sq} . The motor speed ω_r is compared to the reference ω_{ref} and the error is processed by the speed controller to produce a torque command T_e^* .

The stator flux observing adopts ordinary voltage method as:

$$\lambda_{sd} = \int (V_{sd} - i_{sd} R_s) dt \quad (15)$$

$$\lambda_{sq} = \int (V_{sq} - i_{sq} R_s) dt \quad (16)$$

$$|\lambda_s| = \sqrt{(\lambda_{sd}^2 + \lambda_{sq}^2)} \quad (17)$$

The motor torque is calculated from equation (7).

The observing values of stator flux λ_s and motor torque T_e is compared to the reference values λ_s^* and T_e^* respectively, the flux error and torque error is processed by the PI regulator to produce stator reference voltage V_{sd}^* , V_{sq}^* .

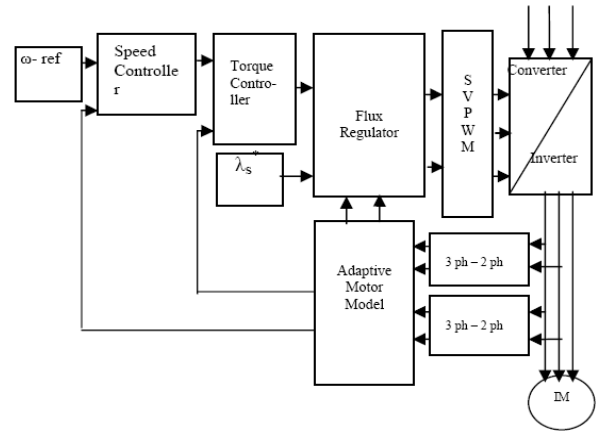


Figure 7. Complete block diagram of SVPWM DTC

4. Results and Discussions

To verify the proposed scheme, a numerical simulation has been carried out on an induction motor drive system by using Matlab/Simulink.

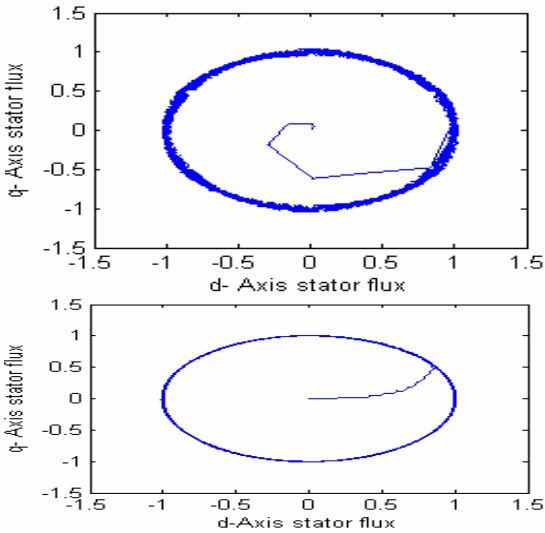


Figure 8. Locus of stator flux during no load (a) Conventional DTC (b) SVPWM DTC

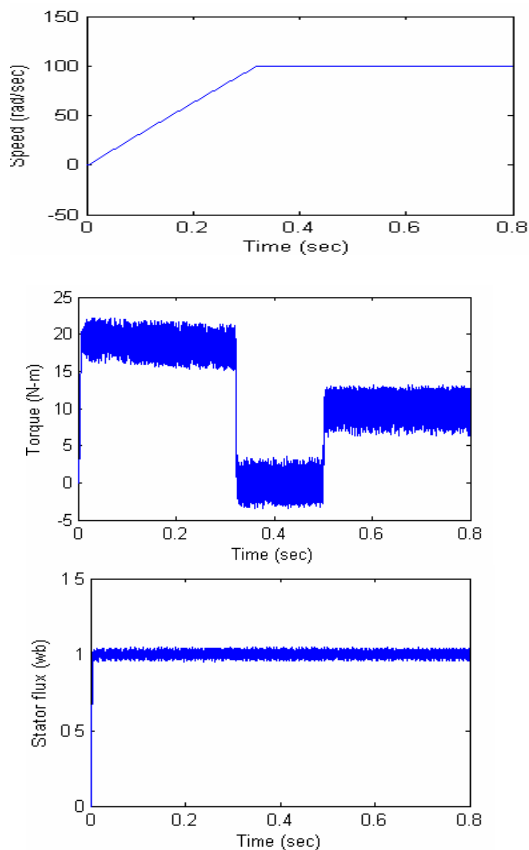


Figure 9. Conventional DTC during step change in torque from 0 to 10 N-m (a) Speed (b) Torque Response (c) Stator Flux

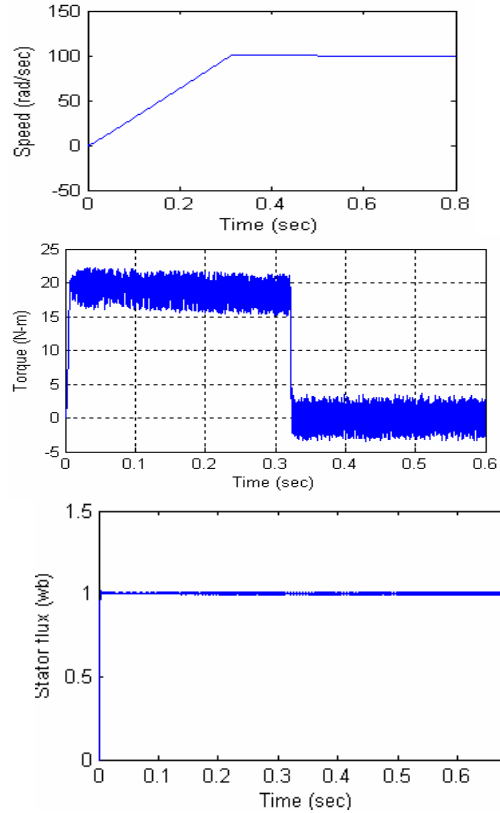


Figure 10. SVPWM DTC during step change In torque from 0 to 10 N-m (a) Speed (b) Torque Response (c) Stator Flux

Figure 9 and Figure 10 shows conventional and proposed scheme with step change in torque from 0 to 10 N-m. From the simulation results, it can be observed that in the proposed drive, there is a significant reduction in torque, current and flux ripples. Hence the harmonic distortion can also reduce.

5. Conclusion

This paper has presented a novel direct torque control method to replace the conventional DTC control method. In this model the flux, torque, speed and angle are estimated by the adaptive motor model. It is possible to determine the switching instants of different space vectors for each sampling period in order to reduce the torque ripples with respect to basic DTC scheme. By analyzing the flux and torque waveforms, it has been shown that lower torque ripple, less current harmonic, constant switch frequency and lower motor oscillation noise. The simulations at different conditions have been carried out and the results show that, the proposed DTC scheme performs well over a wide range of speed.

6. References

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