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Analysis, Evaluation and Simulation of Direct Torque Control of Induction Motor Using SVPWM Technique

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Abstract

Induction machine drive based on Direct Torque Control (DTC) allows high dynamic performance with very simple hysteresis control scheme. Conventional Direct Torque Control (CDTC) suffers from some drawbacks such as high torque ripple and variable switching frequency, difficulties in torque as well as flux control at very low speed. 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. A comparison study between SVPWM-DTC and CDTC is carried out to apply switching select voltage vector. The theoretical foundation principle, the numerical simulation procedure and the performances of both methods are also presented.

Keywords: CDTC, SVM, Hysteresis control, Space vector, Torque ripple

Introduction

With the advancement of power electronics and digital technologies command, several control structures for the AC machines were proposed. Among these structures, the direct torque control has been in recent years towards the most important research and best suited to industrial requirements [2, 3]. The direct torque control (DTC) method has emerged as an alternative to Field Oriented Control (FOC) method for high performance ac drives since it was firstly proposed in the mid 1980. DTC drives utilizing hysteresis comparators suffer from high torque ripple and variable switching frequency.DTC control the torque and speed of the motor, which is directly based on the electromagnetic state of the motor. It only needs to know the stator resistance and terminal quantities (*v* and *i*) in order to perform the stator flux and torque estimations..In 1970s, field oriented control (FOC) scheme proved success for torque and speed control of induction motor. Decoupling of two components of stator currents (flux and torque producing components) is achieved as DC machines to provide independent torque control. Hence the scheme proves itself superior to the DC machine. The problem faced by FOC scheme is complexity in its implementation due to dependence of machine parameters, reference frame transformation.

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. The torque ripple generates noise and vibrations, causes errors in sensor less motor drives, and associated current ripples are in turn responsible for the EMI. The reason of the high current and torque ripple in DTC is the presence of hysteresis comparators together the limited number of available voltage vectors. To reduce the torque ripple, the stator flux vector change, which is demanded to compensate the torque and flux errors, determination should be done and also any voltage vector should be produced by the control mechanism. If a higher number of voltage vectors than those used in conventional DTC is used, the favourable motor control can be obtained..

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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 the conventional DTC of induction motor. Section three presents the proposed SVPWM DTC technique. Section four presents the simulation result and makes some discussion on the simulation results. Section five draws the conclusion.

The Conventional DTC

The basic configuration of the conventional DTC drive proposed by Takahashi is as shown in Fig. 1. It consists of a pair of hysteresis comparator, torque and flux estimators, voltage vector selector and a Voltage Source Inverter (VSI).

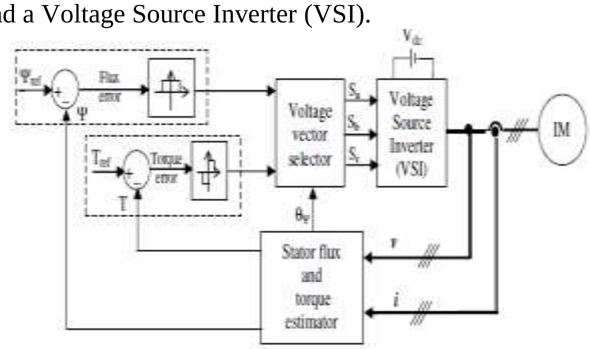

Fig.1 Conventional DTC drive configuration

Stator flux is a time integral of stator EMF

$$\frac{d\Psi_s}{dt} = (V_s - R_s.i_s) \ldots\ldots\ldots.(1)$$

Selection of appropriate voltage vector in the inverter is based on stator equation in stator coordinates

$$\Psi_S = \Psi_S - \Psi_{SO} = \int (V_s - R_s.i_s)\,\mathrm{dt} \ldots\ldots\ldots.(2)$$

Electromagnetic torque can be expressed as

$$\mathrm{T_e} = \frac{3}{2}\frac{\mathrm{p}}{2}\,\Psi_S I_S \ldots\ldots\ldots.(3)$$

$$\Psi_S = \Psi_{qs} - \mathrm{j}\Psi_{ds} \ldots\ldots\ldots.(4)$$

$$\mathrm{I}_s = i_{qs} - ji_{ds} \ldots\ldots\ldots.(5)$$

$$T_e = \frac{3}{2}\frac{p}{2}\frac{L_m}{L_s L_r}\,\Psi_r \mathrm{X} \Psi_s \ldots\ldots\ldots.(7)$$

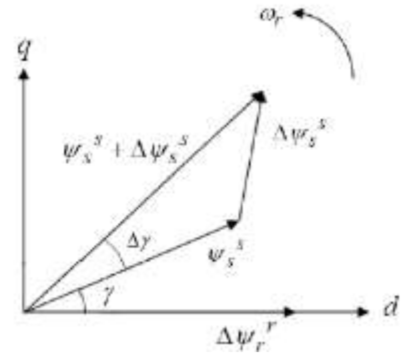

Fig. 2 Stator and rotor flux space vectors

Fig. 2 shows the phasor for Eqn. (5) indicating that the vectors Ψs,Ψr & Is for positive developed torque. If the rotor flux remains constant and the stator flux is changed incrementally by the stator voltage Vs as shown, the corresponding change of γ angle $\Delta\gamma$ and the incremental torque ΔTe is given as

$$T_e = \frac{3}{2}\frac{p}{2}|\Psi_r{}^r||\Psi_s{}^s + \Delta\Psi_s{}^s|\sin(\Delta\delta) \ldots\ldots\ldots.(8)$$

According to the combination of the switching modes of VSI , the voltage vectors are specified for eight different voltage vectors. The switching vectors associated with DTC are shown in Fig. 3. There are six active voltage vectors ($v_{s,1}$-$v_{s,6}$) and two zero voltage vectors ($v_{s,0}$-$v_{s,7}$) at the origin. It can be shown that the voltage vector is given by as:

$$v_s = \frac{2}{3}V_{dc}\left(S_a + S_b e^{\frac{2\pi}{3}} + S_c e^{\frac{4\pi}{3}}\right) \ldots\ldots\ldots(9)$$

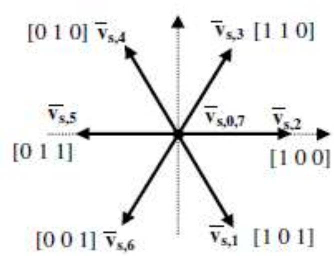

Fig. 3 Voltage space vector

A. Direct Flux Control

The stator flux in stationary frame can be written as

$$\overline{\Psi_s} = \int (\overline{v_s} - \mathrm{R_s}.\overline{\mathrm{i_s}}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots.(10)$$

Analysis is simplified if the stator resistance voltage drop is neglected; hence the flux variation direction is fixed along the selected voltage vector. Over a small period of time, it can be written as:

$$\Delta\Psi_s = v_s.\mathrm{dt} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(11)$$

The stator flux plane is divided into six sectors. Each sector will have a different set of voltage vectors to increase (voltage vector highlighted in gray) or decrease (voltage vector highlighted in black) the stator flux as illustrated in Fig.4. If the stator flux lies in sector *k* then the voltage vector $v_{s,k+1}$ or $v_{s,k+2}$ can be selected to increase or decrease the stator flux. The radial voltage vectors ($v_{s,k}$ and $v_{s,k+3}$),which can be used to quickly affect the flux, are generally avoided. The estimated stator flux is subtracted from the corresponding reference values to obtain the error, which is then fed to the two level hysteresis comparator. The hysteresis comparator will produce flux error status, which can be either 1 or 0.

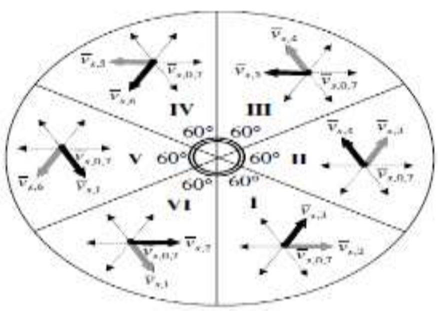

Fig.4 Six equally sectors with different set of voltage vector

B. Direct Torque Control

Eqn (12) gives the instantaneous torque in terms of stator
and rotor flux linkages.

$$T_e = \frac{3}{2}\frac{L_m}{L_s L_r}\overline{\Psi_s \Psi_r} = \frac{3}{2}\frac{L_m}{L_s L_r}\sin\theta_{SR} \ldots\ldots\ldots\ldots(12)$$

The above equation shows that, in order to obtain high dynamic performance it is necessary to vary θ_{SR} quickly. It can be summarized that, assuming the rotor is rotating counterclockwise continuously, the stator flux, which lies in sector *k*, plays an important role in controlling θ_{SR} by applying an appropriate voltage vector as tabulated in Table 1.

C. Switching Selection

Due to the decoupled control of torque and stator flux in DTC, a high performance torque control can be established. If the stator flux lies in sector *k* with the motor rotating in counter clockwise, active voltage vector $v_{s,k+1}$ is used to increase both the stator flux and torque. or $v_{s,k+2}$ is selected to increase the torque but decrease the stator flux.

Table. 1 The variation of θ_{SR} with different voltage vector

Voltage vector	Effect on stator flux	θ_{SR} and T_e
Vs,k+1and Vs,k+2	Stator flx advance forward	Increase
Vs,o and Vs,7	Stator flux weakens	Decrease
Vs,k and Vs,k+3	Stator flux increases or decrease rapidly	Decrease
Vs,k-1 and Vs,k-2	Stator flux rotate inreverse direction	Decreases rapidly

Table. 2 Classical DTC vector table

Flux Error Status	Torque Error Status	S-1	S-2	S-3	S-4	S-5	S-6
0	1	011	001	101	100	110	010
0	0	111	000	111	000	111	000
0	-1	110	010	011	001	101	100
1	1	001	101	100	110	010	011
1	0	000	111	000	111	000	111
1	-1	100	110	010	011	001	101

Proposed SVPWM-DTC technique

SVM techniques have several advantages that are offering better DC bus utilization, lower torque ripple, lower Total Harmonic Distortion (THD) in the AC motor current, lower switching losses, and easier to implement in the digital systems. The torque ripple for this SVMDTC is significantly improved and switching frequency is maintained constant.In this 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.

D. 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 Ψ_s.This can be properly obtained by using a regulator in which the input variable is

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difference between the reference and the estimated flux vectors

$$\Delta\Psi_s = \overline{\Psi_S^*} - \Psi_S \ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

The flux regulator equation can be expressed as follows:

$$\overline{v_S^*} = R_s\,\overline{I_s} + j\omega\overline{\Psi_s} + K_p\Delta\overline{\Psi_s} \ldots\ldots (14)$$

This equation shows that the flux regulator behaves as a proportional controller,and the stator resistant voltage drop in (6) Kp represents the gain of the regulator. The angular frequency w needed in (6) is obtained by the following equation:

$$\omega = \frac{de^{j\theta}}{dt}\, je^{j\theta} \ldots\ldots\ldots\ldots\ldots\ldots (15)$$

E. 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. 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 (l,l,l), 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=l” denotes the upper leg of a phase is switched on, “bc=00” mean the lower legs of band c phases is on. and sectors vectors. The six nonzero vectors divide equally the *d-q* plane into six sectors. The sectors are numbered by S_1& the angle between two adjacent vectors is 60 degrees.

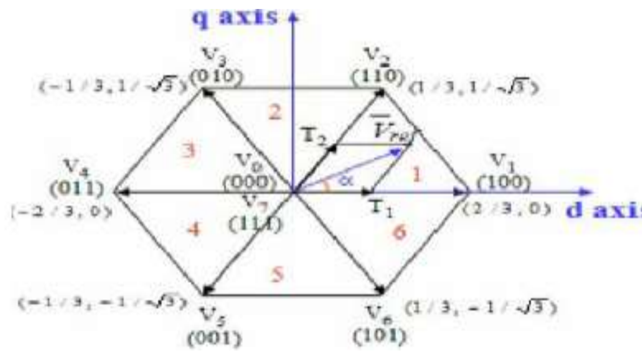

Fig. 5 shows the basic switching vector

Fig. 6 shows the process of compounding Vref 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.

$$T_Z\,\overline{V_{ref}} = T_1\overline{V_1} + T_2\overline{V_2} \ldots\ldots (16)$$
$$T_Z = T_1 + T_2 + T_0 \ldots\ldots\ldots\ldots (17)$$

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 V_{ref}, only helps to balance the turn on and off periods of the transistors, and thus their power dissipation.

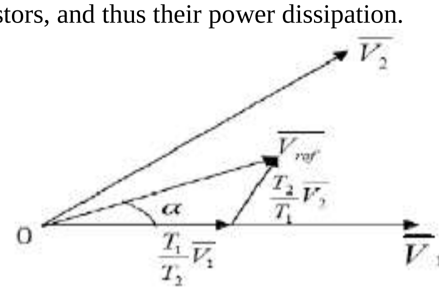

Fig.6 Reference vector as a combination of V1 & V2

Fig.7 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

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transistors S_4,S_6,S_2 lower transistor of the inverter).

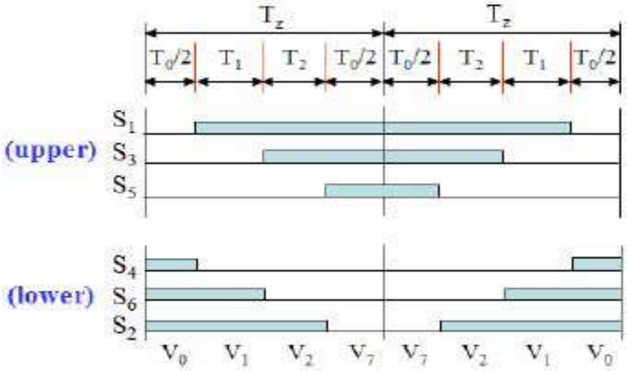

Fig.7 Space Vector PWM Switching pattern in sector

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

$$T_1 = \frac{\sqrt{3}T_Z|\overline{V_{ref}}|}{V_{dc}}\left(\sin\frac{n}{3}\pi\ \cos\alpha - \cos\frac{n}{3}\pi\ \sin\alpha\right) \ldots\ldots(18)$$

$$T_2 = \frac{\sqrt{3}T_Z|\overline{V_{ref}}|}{V_{dc}}\left(-\cos\alpha\sin\frac{n-1}{3}\pi + \cos\frac{n-1}{3}\pi\sin\alpha\right) \ldots(19)$$

$$T_0 = T_Z - T_1 + T_2\ (Where\ n = 1 to 6\ i.e\ sector\ 1\ to\ 6)..(20)$$

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.

F. 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 stator voltages Vabc and stator currents Iabc are converted into two-phase voltages Vsd,Vsq and currents Isd, Isq. 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 Te^* .
.The stator flux observing adopts ordinary voltage method as:

$$\Psi_{sd} = \int (V_{sd} - i_{sd}R_s)\ dt \ldots\ldots\ldots\ldots\ldots (21)$$

$$\Psi_{sq} = \int (V_{sq} - i_{sq}R_s)\ dt \ldots\ldots\ldots\ldots\ldots (22)$$

$$|\Psi_s| = \sqrt{(\Psi_{sd}^2 - \Psi_{sq}^2)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (23)$$

The motor torque is calculated from equation .The observing values of stator flux Ψs and motor torque Te is compared to the reference values Ψ*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. .

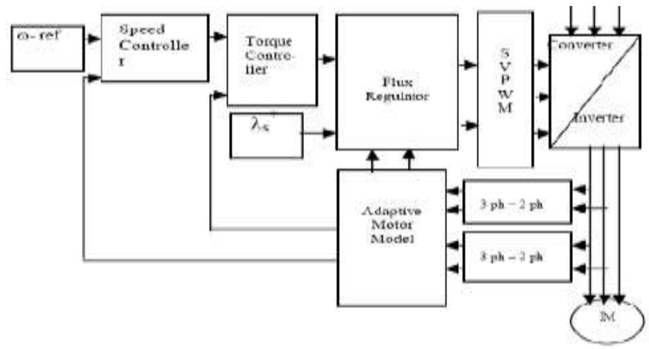

Fig. 8 Complete block diagram of SVPWM DTC

Interpretation and result

To study the performance of the SVM-DTC with direct torque control strategy, the simulation of the system was conducted using MATLAB. Simulation results for a DTC system when controlling the 3-phase induction machine having parameter is also shown below.

Conclusion

In this paper a SVPWM_DTC of induction machine have been proposed. In classical DTC, as the torque ripple is maintained within hysteresis band, switching frequency changes with speed. An improved torque response was achieved with the SVPWM_DTC than the conventional DTC. The performance. using simulation. The main improvements shown are reduction of torque ripples in transient and steady state response.

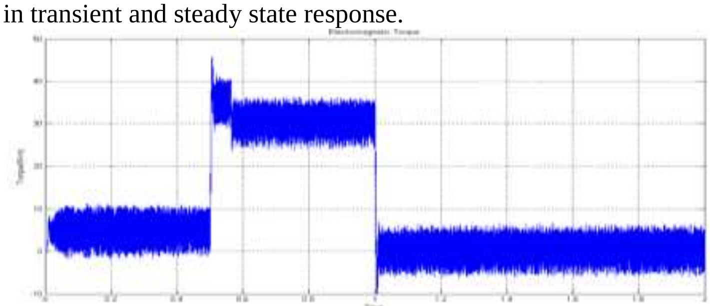

Fig 9 Simulation results of classical DTC;30 N-m load is applied at0.5secandremovedat0.7sec

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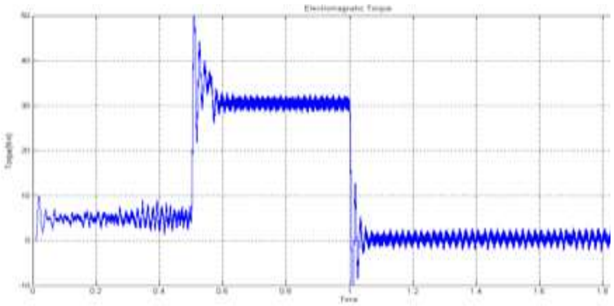

Fig. 10 Simulation results of SV PWM_ DTC; a 30 N-m load is applied at 0.5 sec and removed at 0.7 sec.

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