DTC-SVM Scheme for Induction Motors Fed with a Three-level Inverter

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Abstract—Direct Torque Control is a control technique in AC drive systems to obtain high performance torque control. The conventional DTC drive contains a pair of hysteresis comparators. DTC drives utilizing hysteresis comparators suffer from high torque ripple and variable switching frequency. The most common solution to those problems is to use the space vector depends on the reference torque and flux. In this Paper The space vector modulation technique (SVPWM) is applied to 2 level inverter control in the proposed DTC-based induction motor drive system, thereby dramatically reducing the torque ripple. Then the controller based on space vector modulation is designed to be applied in the control of Induction Motor (IM) with a three-level Inverter. This type of Inverter has several advantages over the standard two-level VSI, such as a greater number of levels in the output voltage waveforms, Lower dV/dt, less harmonic distortion in voltage and current waveforms and lower switching frequencies. This paper proposes a general SVPWM algorithm for three-level based on standard two-level SVPWM. The proposed scheme is described clearly and simulation results are reported to demonstrate its effectiveness. The entire control scheme is implemented with Matlab/Simulink.

Keywords—Direct torque control, space vector Pulsewidth modulation(SVPWM), neutral point clamped(NPC), two-level inverter.

I. INTRODUCTION

IN recent years, many studies have been carried out to develop different solution for the induction motor control having the features of precise and quick torque response and reduction of complexity of the field-oriented algorithms. The direct torque control (DTC) technique has been recognized as viable solution to achieve these requirements.

However, the main limit of conventional DTC scheme is high torque ripple, variable switching frequency, and the mean torque output, which does not match the torque demand [1].

A variety of techniques have been proposed to overcome some of the drawbacks present in DTC [2]. Some solution proposed are: DTC with Space Vector Modulation(SVPWM) [3]; the use of a duty-ratio controller to introduce a modulation between active vectors chosen from the look-up table and the zero vectors [4-5]; use of artificial intelligence techniques, such as Neuro-Fuzzy controller with SVPWM [6]. However the complexity of the control is considerably increased.

A different approach to improve DTC features is to employ different inverter topologies (Multilevel Inverter) from the standard two-level VSI.

Multilevel inverters are increasingly being used in high-power medium voltage applications due to their superior performance compared to two-level inverters, such as lower common-mod voltage, lower dV/dt, lower harmonic in output voltage and current, greater number of levels in the output voltage waveforms, and reduced voltage on the power switches[7].

Among various modulation techniques for a multilevel inverter, space vector pulsewidth modulation (SVPWM) is an attractive candidate due to following merits. It directly uses the control variable given by the control system and identifies each switching vector as a point in complex (α, β) space. It is suitable for digital signal processor (DSP) implementation. It can optimize switching sequences.

In this paper three different DTC schemes will be compared with each other. These three schemes are Classical DTC with switching table, DTC-SVM with two-level inverter, and DTC-SVM with three-level inverter. The Proposed scheme is described clearly and simulation results are reported to demonstrate its effectiveness. The entire control scheme is implemented with Matlab/Simulink.

II. DIRECT TORQUE CONTROL SCHEMES

A. Classical DTC Scheme

The fundamental idea of DTC is to control both the torque and the magnitude of flux within the associated error bands in real time. In order to understand DTC principle some of the equations of the Induction motor need to be reviewed. The electromagnetic torque can be expressed as a function of the stator flux and the rotor flux space vectors as follows:

$$Te = -\frac{3}{2}P\frac{L_m}{L_sL_r - L_m^2}\vec{\psi}_s \times \vec{\psi}'_r. \tag{1}$$

If the modulus of the previous expression is evaluated it is obtained:

$$Te = \frac{3}{2}P\frac{L_m}{L_sL_r - L_m^2}|\vec{\psi}'_r||\vec{\psi}_s|\sin(\gamma_s - \gamma_r). \tag{2}$$

Considering the modulus of rotor and stator fluxes constant, torque can be controlled by changing the relative angle between both flux vectors. Stator flux can be adjusted by stator voltage equation in stator fixed coordinates:

$$\vec{V}_s = \vec{R}_s\vec{i}_s + \frac{d\vec{\psi}_s}{dt}. \tag{3}$$

If the voltage drop in the stator resistance is neglected the

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variation of the stator flux is directly proportional to the stator voltage applied:

$$\vec{V}_s \propto \frac{d\vec{\psi}_s}{dt}. \qquad (4)$$

Because the rotor time constant is larger than the stator one, the rotor flux changes slowly compared to the stator flux. Thus torque can be controlled by quickly varying the stator flux position by means of the stator voltage applied to the motor. The desired decoupled control of the stator flux modulus and torque is achieved by acting on the radial (x) and tangential (y) component respectively of the stator flux vector. According to (5) these two components will depend on the components of the stator voltage vector applied in the same directions. The tangential component of the stator voltage will affect the relative angle between the rotor and the stator flux vectors and in turns will control the torque variation according to (2).

The redial component will affect the amplitude of the stator flux vector.

Fig. 1 shows the stator flux in the α-β plane, and the effect of the different states of a two level VSI according to torque and stator flux modulus variation.
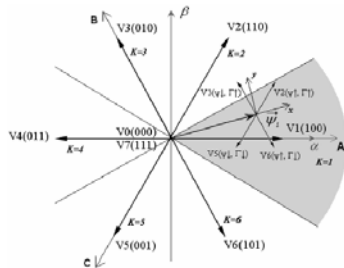

Fig. 1 Influence of the voltage vector selected on the variation of stator flux modulus and torque

According to the consideration illustrated in Fig. 1 the generic and or classical DTC scheme for a VSI-fed Induction Motor was developed a shown in Fig. 2.
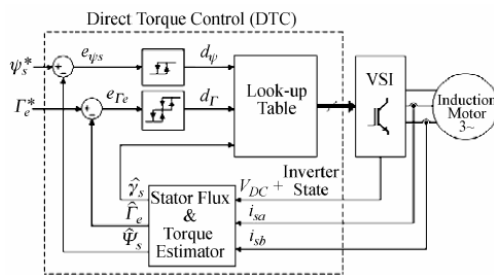

Fig. 2 Classical DTC scheme

As it can be seen, there are two different loops related to the magnitudes of the stator flux modulus and torque. The reference values for the stator flux modulus and the torque are compared with the estimated values, the resulting error values are fed into a level into a two-level and a three-level hysteresis block respectively. The outputs of the stator flux error and torque error hysteresis block, together with the position of the stator flux are used as inputs to the look-up Table I.

TABLE I
CLASSICAL DTC LOOK-UP TABLE

K(γs)		1	2	3	4	5	6
dψ =1	dT = 1	V2	V3	V4	V5	V6	V1
	dT = 0	V7	V0	V7	V0	V7	V0
	dT = -1	V6	V1	V2	V3	V4	V5
dψ = -1	dT = 1	V3	V4	V5	V6	V1	V2
	dT = 0	V0	V7	V0	V7	V0	V7
	dT = -1	V5	V6	V1	V2	V3	V4

The principle of DTC operation can also be explained by analysing the Induction Motor stator voltage equation in the stat-or flux reference frame.

$$\vec{V}_s = R_s\vec{i}_s + \frac{d\vec{\psi}_s}{dt} + j\omega_s\vec{\psi}_s. \qquad (5)$$

If this expression is separated into the direct (x) and the quadrature component (y) of the stator voltage, the following expression can be obtained:

$$V_{sx} = R_s i_{sx} + \frac{d\psi_{sx}}{dt} \qquad (6)$$

$$V_{sy} = R_s i_{sy} + \omega_s\psi_{sx}. \qquad (7)$$

From use of expression (8) the following torque expression is obtained:

$$T_e = \frac{3}{2}P\frac{\psi_{sx}(V_{sy} - \omega_s\psi_{sx})}{R_s}. \qquad (8)$$

Electromagnetic torque can be controlled by means of the component of the stator voltage, under adequate decoupling of the stator flux.

DTC requires the estimation of stator flux and torque, which can be performed by means of two different phase currents, the state of the VSI and the voltage level in the DC-link. This estimation is based in the stator voltage equation [8]:

$$\vec{\psi}_s = \int(\vec{V}_s - R_s\vec{i}_s)dt. \qquad (9)$$

B. DTC-SVM with Two-Level Inverter

In this scheme there are two proportional integral (PI) type controllers instead of hysteresis band regulate the torque and the magnitude of flux. As shown in Fig. 3, two proportional integral (PI) type controllers regulate the flux amplitude and the torque, respectively. Therefore, both the torque and the magnitude of flux are under control, thereby generating the voltage command for inverter control. Noting that no decoupling mechanism is required as the flux magnitude and the torque can be regulated by the PI controllers. Due to the structure of the inverter, the DC bus voltage is fixed, therefore the speed of voltage space vectors are not controllable, but we can adjust the speed by means of inserting the zero voltage vectors to control the electromagnetic torque generated by the induction motor. The selection of vectors is also changed. It is not based on the region of the flux linkage, but on the error vector between the expected and the estimated flux linkage

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vectors [1].

Fig. 3 DTC-SVM scheme

The objective of Space Vector switching is to appropriate the sinusoidal line modulating signal (reference voltage vector) V_s^*, with the eight space vector (V_n, n=0,1,…7). These eight space vectors form a hexagon (Fig. 4) which can be seen as consisting of six sector spanning 60˚ each.

Fig. 4 Phase voltage space vector

The reference vector which represents three-phase sinusoidal voltage is generated using SVPWM by switching between two nearest active vectors and zero vector. To calculate the time of application of different vectors, consider Fig. 5, depicting the position of different available space vectors and the reference vector in the first sector.

Fig. 5 Principle of space vector time calculation

The time of application of active space voltage vectors is found from Fig. 4 as:

$$t_a = \frac{\left|\overline{v}_s^*\right|}{\left|\overline{v}_a\right|} \frac{\sin(\pi/3 - \alpha)}{\sin(2\pi/3)}. \qquad (10)$$

$$t_b = \frac{\left|\overline{v}_s^*\right|}{\left|\overline{v}_b\right|} \frac{\sin(\alpha)}{\sin(2\pi/3)}. \qquad (11)$$

$$t_0 = t_s - t_a - t_b. \qquad (12)$$

Where $\left|\overline{v}_a\right| = \left|\overline{v}_b\right| = (2/3)Vdc.$ In order to obtain fixed switching frequency and optimum harmonic performance from SVPWM, each leg should change its state only once in one switching period. This is achieved by applying zero state vector followed by two adjacent active state vector in half switching period. The next half of the switching period is the mirror image of the first half. The total switching period is divided intro 7parts, the zero vector is applied for 1/4th of the total zero vector time first followed by the application of active vectors for half of their application time and then again zero vector is applied for 1/4th of the zero vector time. This is then repeated in the next half of the switching period. This is how symmetrical SVPWM is obtained. The leg voltage in one switching period is depicted in Fig. 6 for sector I.

Fig. 6 Leg voltages and space vector disposition in sector I

The sinusoidal reference space vector form a circular trajectory inside the hexagon. The largest output voltage magnitude that can be achieved using SVPWM is the radius of the largest circle that can be inscribed within the hexagon[9].

$$\left|\overline{v}_s^*\right| = \frac{2}{3}V_{dc}\cos(\pi/6) = \frac{1}{\sqrt{3}}V_{dc}. \qquad (13)$$

C. DTC-SVM with Three-Level Inverter

In this scheme the block diagram is exactly like Fig. 3 but the only difference between two scheme is that three-level inverter will be replaced instead of two-level inverter. Multilevel inverters are increasingly being used in high-power medium voltage applications due to their superior performance compared to two-level inverters, such as lower common-mode voltage, lower dv/dt, lower harmonics in output voltage and current, and reduced voltage on the power switches.

Among various modulation technique for a multilevel inverter, space vector pulsewidth modulation (SVPWM) is an attractive candidate due to the following merits. It directly uses the control variable given by the control system and identifies each switching vector as a point in complex (α, β) space. It is suitable for digital signal processor (DSP) implementation. It can optimize switching sequences.

Fig. 7 shows the space vector diagram of a three-level inverter. There are six sectors (S_1-S_6), four triangles (Δ_0-Δ_3) in a sector, and a total of 27 switching states in this space vector diagram.

As a method outlined in [7] suggests, each sector of the outer hexagon of three-level SVM can be divided into four smaller triangles, indexed as shown in Fig. 8. Each of these

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smaller triangles are then considered as one sector of a two-level hexagon, with the same redundancy at the origin.
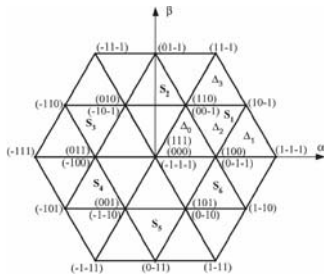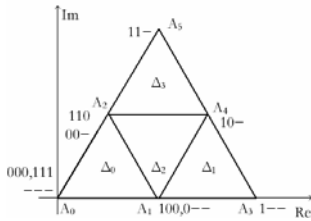

Fig. 7 Space vector diagram of three-level inverter

Fig. 8 Division of each sector to four triangles

In this method, the triangle that bounds the reference vector is found based on coordinates of the tip of the reference vector. The origin (0, 0) is then moved to the origin-vertex of the corresponding triangle.

The triangles are determined by firs calculating auxiliary parameters k_1 and k_2 which are defined as:

$$k_1 = \left\lfloor V_\alpha + \frac{V_\beta}{\sqrt{3}} \right\rfloor. \qquad (14) \qquad k_2 = \left\lfloor \frac{V_\beta}{\frac{\sqrt{3}}{2}} \right\rfloor. \qquad (15)$$

V_α and V_β are coordinates of the tip of the space vector, k_1 determines whether the small triangle is in the right-hand side of the sector ($k_1=1$) or in the left-hand side ($k_1=0$). k_2 determines if it is in the upper half ($k_2=1$) or in the lower half ($k_2=0$).

The reference vector is shifted to the new set of axes that intersect at the main vertex (or origin) of the triangle. Assuming a type one triangle, the coordinates of the tip of the shifted reference vector $\overline{A_iP}$, where P= (V_α, V_β) is the tipoff the original space vector and A_i is the origin of the triangle, are found as follows.

$$V_{\alpha i} = V_\alpha - k_1 + \frac{1}{2}k_2. \qquad (16)$$

$$V_{\beta i} = V_\beta - \frac{\sqrt{3}}{2}k_2. \qquad (17)$$

The triangle index is found from:

$$\Delta = k_1^2 + 2k_2. \qquad (18)$$

Once the shifted reference is found, time shares are

calculated similar to the two-level case. Using shifted coordinates, T_a (duration of the space-vector aligned with the α-axis), T_b (duration of the space-vector at 60° from the α-axis) and T_z (duration of zero space-vectors) can be found from the following.

$$T_a = T_s (V_{\alpha i} - \frac{V_{\beta i}}{\sqrt{3}}) \qquad (19)$$

$$T_b = T_s (\frac{V_{\beta i}}{\frac{\sqrt{3}}{2}}) \qquad (20)$$

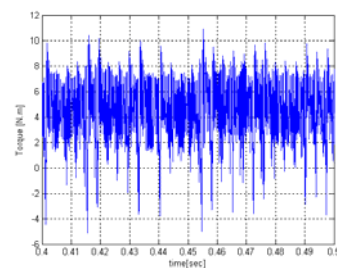$$T_z = T_s - T_a - T_b. \qquad (21)$$

The three nearest space vectors are used to synthesize the reference vector. These vectors correspond to the vertices of the bounding triangle.

The sequence of vectors in the first sector is determined by inspection. For other sectors, the states are found from the mapping of switching states between the first sector and other sectors. The switch states are left unchanged for the first sector, but for other sectors they are changed accordingly so that they use the available space-vector in other sectors.
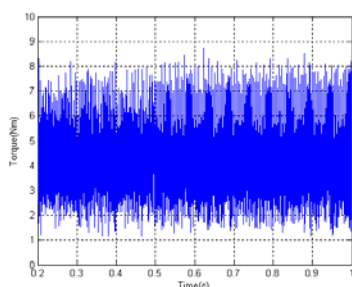
For maintaining the balance of capacitor voltages, the space vector sequences can be chosen in a way that the available redundancies lead to sharing of current of each leg equally between the respective capacitors.
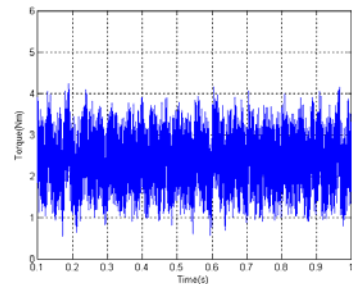
III. SIMULATION RESULTS

To show the effectiveness of the DTC-SVM with three-level inverter and SVPWM switching technique a simulation work has been carried out on induction motor with the specifications given in Appendix. The proposed scheme is simulated with Matlab/Simulink. Fig. 9 shows the simulation results. Fig. 9(a) shows the torque response for Classical DTC, here the torque ripple is around 14 Nm. Fig. 9(b) shows the torque response with the DTC-SVM with two-level inverter scheme with the same load torque, from this response it is observed that the ripple in the torque response is around 7.4 Nm. Fig. 9(c) shows the torque response with the DTC-SVM with three-level inverter scheme with the same load torque, here the torque ripple is around 3.5 Nm. This results show that the torque ripple in the three-level scheme has been reduced significantly. Table II shows the comparative analysis of torque ripple.

(a) Classical DTC

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(b) DTC-SVM (Two-level Inverter)

(c) DTC-SVM (Three-level Inverter)
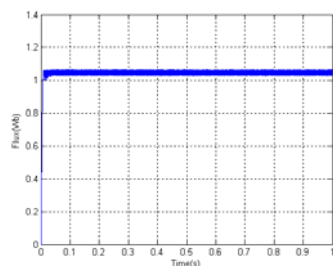Fig. 10 Stator Flux response

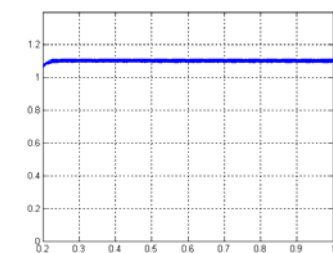(c) DTC-SVM (Three-level Inverter)
Fig. 9 Torque Response

TABLE I I
COMPARATIVE ANALYSIS OF TORQUE RIPPLE

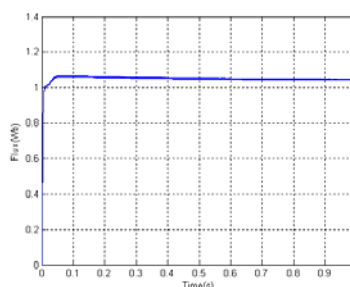| Torque Ripple in Classical DTC	Torque Ripple in DTC-SVM with two-level inverter	Torque Ripple in DTC-SVM with three-level inverter
14 Nm	7.4 Nm	3.5 Nm

From the simulation results presented in Fig. 10 it is apparent that the flux ripple for the new system utilizing a three-level inverter with SVPWM switching is considerably reduced.

(a) Classic DTC

(b) DTC-SVM (Two-level Inverter)

IV. CONCLUSION

In this paper the DTC principle is presented and it is shown that with a simple SVPWM algorithm for a three-level inverter based on a standard two-level inverter we can implement this method easily. The simulation results obtained for the DTC-SVM with three level inverter illustrate a considerable reduction in torque ripple and flux ripple compared to the existing classical DTC system and DTC-SVM utilizing two-level inverter.

APPENDIX

Motor parameter used in the simulation:
Induction Motor Detail
400V, 10HP(7.5KW), 4 Poles, 1440 rpm

Stator resistance	0.7384 ohm
Stator inductance	3.045 mH
Moment of inertia	0.0343 kg.m^2
Friction coefficient	0.000503 N.m.s/rad

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