Implementation of Direct Torque Control Induction Motor Drive using MATLAB

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Abstract— This paper describes how space vector pulse width modulation can be realized in direct control method by maintaining the hysteresis band of the stator flux path in a proper way. This band is varied in predefined way which depends on the angle of the reference voltage vector.

Keywords— Direct torque control, space vector pulse width modulation, hysteresis band controller.

I. Introduction

With the continuous improvement of technology in power electronics and micro-electronics, variable voltage and variable frequency ac motor drives have come to increased use in various industrial applications. These new approaches need a simple method of control for ac motors. Control of ac motors become very popular because it is possible to obtain the characteristics of dc motors by improving control techniques. It is well-known that the control method of an ac motor is comparatively more difficult to realize because of involvement of various controllable parameters like voltage, current, frequency, torque, flux and so on. Though it is possible to achieve almost the same characteristics of dc motor using induction motor, it is very complicated to realize because of need for on line co-ordinate transformation and continuous need of either speed or position signal. Particularly, field oriented control, which guarantees high dynamic and static performance like dc motor drives, has been very popular and has constantly being developed and improved. But the innovative idea of co-ordinate transformation and the analogy with dc motor control. This substituted non-linear co-ordinate transformation in field oriented control by self control of stator flux and torque. In contrast to the control of the direct and quadrature component stator currents to maintain desired flux and torque respectively, this scheme directly controls those two parameters in stationery frame, while currents and voltages are regulated indirectly. As the concept of instantaneous space vector becomes very popular, ac drives controllers will use this tool as a PWM technique. Moreover, since quick accelerating and decelerating rotation of stator flux vector is achieved, rapid torque response can be obtained.

To achieve this, both torque and flux controllers employ hysteresis band with the objective to maintain both the machine variables within their respective tolerance bands. Due to direct application of active voltage vector by the modulator, sometimes stator voltage vector moves very fast tangentially along the circular path of stator flux vector within the flux hysteresis band leading to non-sinusoidal voltage across the stator terminal. This introduces some harmonic voltages leading to increased loss of the machine. So, the concentration should be given on the generation of pulse width modulation waveform such that the inverter output voltage magnitude can be maintained close to sinusoidal wave shape averaged over switching sub-cycle.

II. Space Vector Concept

As we know a single vector known as space vector can be represent a set of three phase vectors. The transformation three-phases to stationary d-q frame are given by following equation.

$$\begin{bmatrix} Vd \\ Vq \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \quad (1)$$

With further simplification, we get

$$[\overline{V}] = \sqrt{\frac{2}{3}}[Va - 0.5(Vb + Vc)] + j\,\frac{1}{\sqrt{2}}[Vb - Vc] \quad (2)$$

This constant $\sqrt{\frac{2}{3}}$ comes into picture in order to maintain power and impedance matrix invariance between transformation.
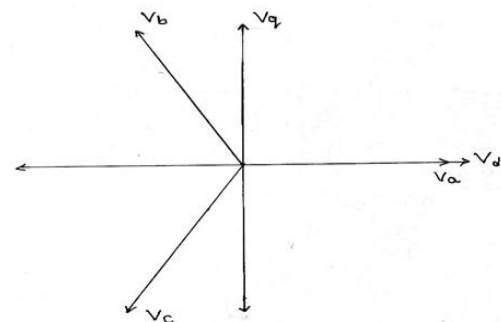

Fig. 1.1. Transformation for 3-ph to stationary d-q axis.

Consider a 3-phase inverter shown in figure 1.2. It is well-known that the three phase inverter can be produce 8 output states. For all possible switching states, corresponding phase voltage & the voltage space vector are shown in the following table (1). Switching states 100 means, upper switching phase 'a' is closed and upper switch in phase 'b'& 'c' are open. Thus 8 output states of inverter represent 8 space vectors, two vectors i.e.V7[000] &V8[111] are null & remaining 6 are of equal magnitude & arranged 60^0 apart in space diagram as shown in fig. 1.3. Switching stages are shown in fig. 1.5.

By considering the six pulse VSI shown in figure, there are six nonzero active voltage switching space vectors and two

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zero space vectors. There are shown in figure shows the corresponding 8 switching states. The switching voltage space vector shown in fig. 1.4.
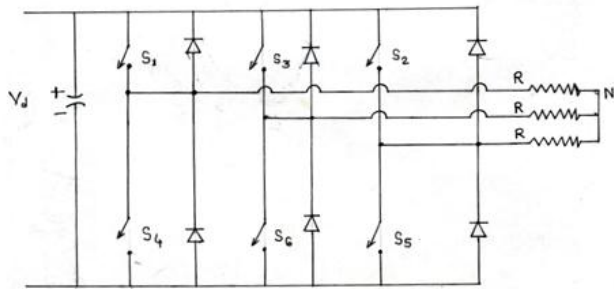

Fig. 1.2. Phase voltage source inverter with balanced resistive load.
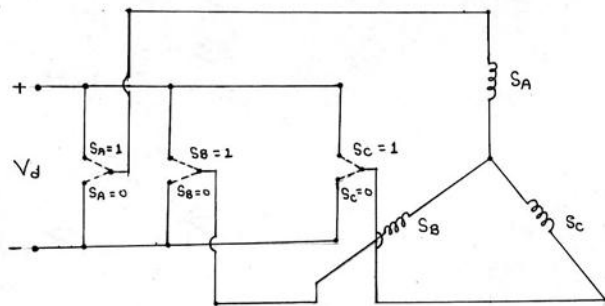

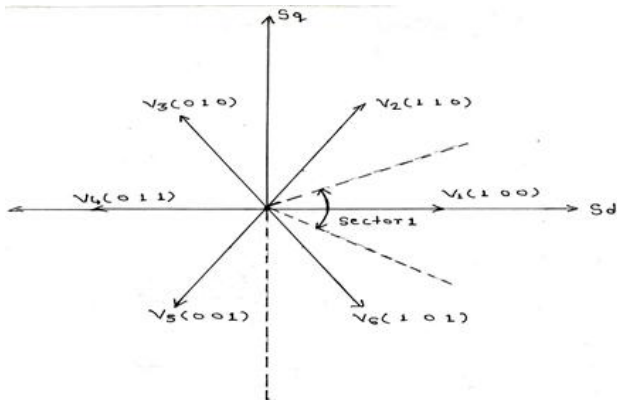Fig. 1.3. Three phase VSI with induction motor.

Fig. 1.4. Switching voltage space vector.

TABLE 1.1 Table showing different switching states; corresponding phase voltages & space vector.

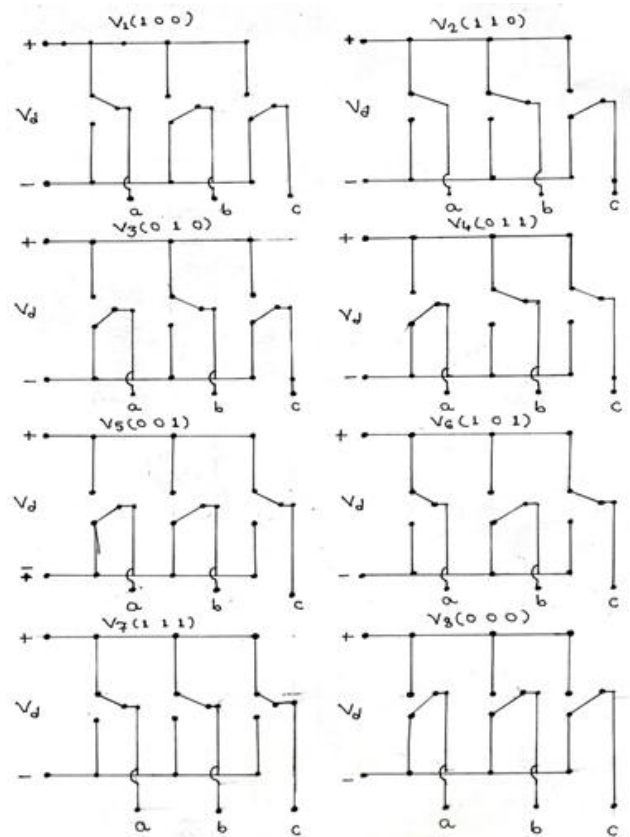| Switching States	Phase Voltages			Voltage Vector
	Van	Vbn	Vcn	
[0 0 0]	0	0	0	V0
[1 0 0]	2Vd/3	-Vd/3	- Vd/3	V1
[1 1 0]	Vd/3	Vd/3	-2Vd/3	V2
[0 1 0]	-Vd/3	2Vd/3	- Vd/3	V3
[0 1 1]	-2Vd/3	Vd/3	Vd/3	V4
[0 0 1]	-Vd/3	-Vd/3	2Vd/3	V5
[1 0 1]	Vd/3	-2Vd/3	Vd/3	V6
[1 1 1]	0	0	0	V7

Fig. 1.5. Switching states.

III. PRINCIPLE OF DIRECT TORQUE CONTROL

The block diagram of direct torque control of induction motor is shown in figure 1.6 finding how the table of switching is generated in the way to a successful explanation.
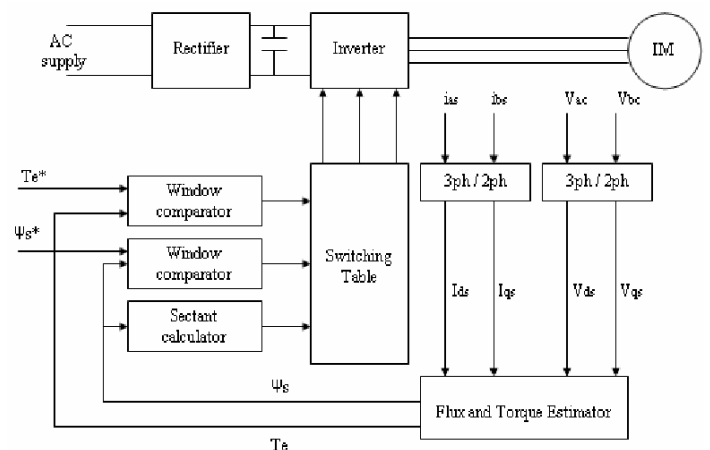

Fig. 1.6. Block diagram showing principle of direct torque control.

Selection of appropriate voltage vector $V_s(i)$ in the inverter is based on stator equations in stator co –ordinates.

$$V_s = i_s R_s + \frac{d\psi_s}{dt}$$

$$\psi_s = \int (V_s - i_s R_s)$$

(3)

$$\psi_s = \int V_s \qquad (4)$$

In essence the stator flux acceleration or decelerations can cancel torque error. To reduce the flux error, the flux trajectory will be drawn along appropriate voltage vectors that will increase or decrease the flux amplitude .When the flux amplitude has to be increased a voltage vector phase shifted by an angle larger than 90^0 with respect to existing flux vector Ψs_0 is applied .In contrast, if flux amplitude has to be reduced, an angle less than 90^0 will be applied .For the flux space phases in the first sector, the voltage vector selection is shown in figure 1.7. As shown in figure 1.6, the direct torque control scheme uses the feedback control of torque and stator flux linkages which are computed from the measured motor voltage and currents.

IV. ESTIMATION PROBLEM

In DTC induction motor drive the stator flux linkage components have to be estimated due to two reasons. 1. These components are required in the optimum switching vector selection table. 2. They are also required for the estimation of the electromagnetic torque. It should be noted that, in general, it follows directly from the stator voltage equation in the stator reference frame that;

$$\psi_{ds} = \int (V_{ds} - Rs.Ids)dt \qquad (5)$$

$$\psi_{qs} = \int (V_{qs} - Rs.Iqs)dt \qquad (6)$$

And as shown below;

$$\psi_{sB} = \frac{\sqrt{3}}{2}(\psi_{ds} - \psi_{qs}) \qquad (7)$$

If the non-power variance form of the space vector are used, then

$$\psi_{ds} = \int (V_{ds} - Rs.Ids)dt \qquad (8)$$

Where, $Vds = VsA \ \& \quad Ids = IsA$

Furthermore,

$$\psi_{qs} = \frac{\psi_{sB} - \psi_{sC}}{\sqrt{3}} = \int (Vqs - Rs.Iqs)dt \qquad (9)$$

It is more necessary to use three stator-voltage sensor & three stator current sensors since it is possible to show, by considering

$$V_{SA} + V_{SB} + V_{SC} = 0 \qquad (10)$$

$$I_{SA} + I_{SB} + Isc = 0 \qquad (11)$$

That $Vds \ \& \ Vqs$ can be obtained monitoring only two stator line voltages and $Ids \ \& \ Iqs$ can be obtained by monitoring only two stator currents.

Thus,

$$Vds = 1/3(V_{AB} + V_{BC}) \qquad (12)$$

$$Vqs = -(V_{AB} + V_{BC})/\sqrt{3} \qquad (13)$$

$$Ids = Ibs \qquad (14)$$

$$Iqs = (Ibs + 2Ics)/\sqrt{3} \qquad (15)$$

It is very important to note that the performance of the DTC drive using equations will depend greatly on the accuracy of the estimated stator flux linkage component, these depends on the accuracy of the monitored voltage and currents.

V. STATOR-FLUX BASED DTC INDUCTION MOTOR DRIVE

The scheme uses the stator reference frame model of the induction motor and the same reference model is used in the implementation thereby avoiding the trigonometric operation in the co-ordinate transformations of the reference frame. The stator d & q axis flux linkage Ψ_{ds}, Ψ_{qs} can be obtained through integration of the difference between the phase voltage and the voltage drop in the stator resistance as given in the equations. The flux linkage space vector is essentially dot product of Ψ_{ds} & Ψ_{qs}.

$$\psi_s = \sqrt{(\psi_{qs}^2 + \psi_{ds}^2)} \angle \left\{ \theta_s = \tan^{-1}\left(\frac{\psi_{qs}}{\psi_{ds}}\right) \right\}$$

☐the electromagnetic torque is given by

$$Te = \frac{P}{2} \cdot \frac{3}{2}(\psi_{ds.}I_{qs} - \psi_{qs.}I_{ds}) \qquad (16)$$

Where the direct & quadrature axis components are obtained from there three phase quantities using the following transformation.

$$\begin{bmatrix} Ids \\ Iqs \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & 0.866 & -0.866 \end{bmatrix} \begin{bmatrix} IsA \\ IsB \\ IsC \end{bmatrix} \qquad (17)$$

VI . OPTIMUM SWITCHING VECTOR SELECTION

Optimum selection of the switching vectors for all the possible stator flux-linkage space vector positions (six positions, corresponding to the six sectors) is shown in table 1.2. Where sector 1 is the range of Θ (1), sector 2 is the range of Θ (2)… Sector 6 is the range of Θ (6), the desired control inputs. If a stator flux increase is required the dΨ =1; If a stator flux increase is required the dΨ =0;

The rotation corresponds to the facts that the digital output signals of a two level flux hysteresis comparator are dΨ. Where,

$$d\Psi = 1 \ if \ |\Psi s| \le |\Psi sref| - |\Delta\Psi s|$$
$$d\Psi = 1 \ if \ |\Psi s| \ge |\Psi sref| + |\Delta\Psi s| \qquad (18)$$

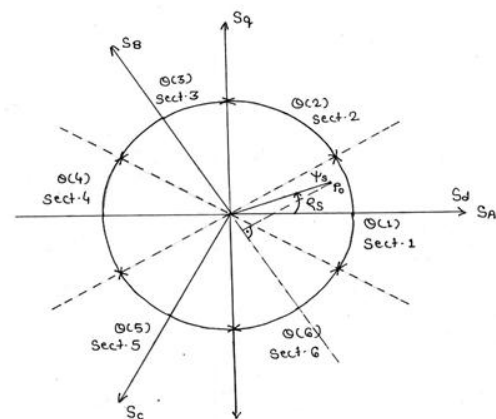

Fig. 1.7. Relationship of the space vector, 'Ψs' to the stator flux-linkage components Ψds, Ψqs.

The selection of width of hysteresis bands has important effects; a too small value may have effect of losing the control. The stator flux linkage may exceeds the value required by the tolerance band, the width of which is $2\lceil\Delta\Psi s\rceil$ .the duration of the zero states directly influence the torque oscillation.

The optimum switching look up table requires the knowledge of position of the stator-flux linkage space vector; since it must be known in which sector is the stator flux linkage space vector. For this purpose the angles Θ (1), Θ (2)… Θ (6), shown in the fig.5 (b) are required. The stator flux angle (ρ_s) can be determine by using the estimated value of the direct axis & quadrature axis stator flux in the stationary reference frame (Ψds, Ψqs), thus,

$$\rho_s = \tan^{-1}\left(\frac{\psi_{qs.}}{\psi_{ds.}}\right) \tag{19}$$

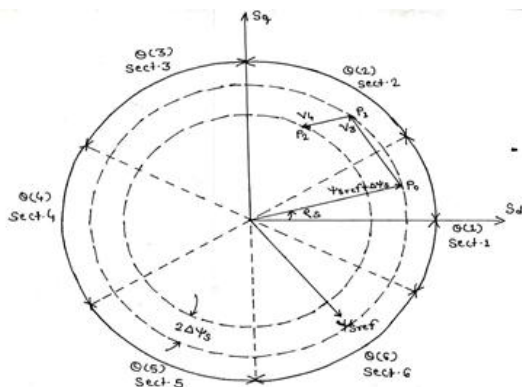The angle ρ_s can be used to obtain the angles Θ (1), Θ (2)… Θ (6).

Fig. 1.8. Control of the flux linkage space vector inverter switching vector.

TABLE 1.2. optimum voltage switching vector look up table.

Ψs	dTe	α 1 sector1	α 2	α 3	α 4	α 5	α 6
1	1	V2	V3	V4	V5	V6	V6
	0	V7	V0	V7	V0	V7	V7
	-1	V6	V1	V2	V3	V4	V4
0	1	V3	V4	V5	V6	V1	V1
	0	V0	V7	V0	V7	V0	V0
	-1	V5	V6	V1	V2	V3	V3

For table :-
Active switching vectors:-
V1 [100]   V2 [110]   V3 [010]   V4 [011]   V5 [001]   V6 [101]
Zero switching vectors:-
V7 [111], V8 [000]

VI. POSITION OF STATOR FLUX-LINKAGE SPACE VECTOR

In general, it can be seen that, if an increase of torque is required, then the torque is controlled by applying the voltage vectors that advance the flux linkage space vector in the direction of rotation and if a decrease is required voltage vector are applied which oppose the direction of the torque. If zero switching vector is applied (V7 or V8), & shown in fig (6); which minimizes the inverter switching. It follows that the angle of the stator voltage space vector is indirectly controlled through the flux-vector modulus and torque and increasing

torque causes an increased angle. The torque demand is reduced to a choice of increasing (positive torque), decrease (negative torque), or zero.
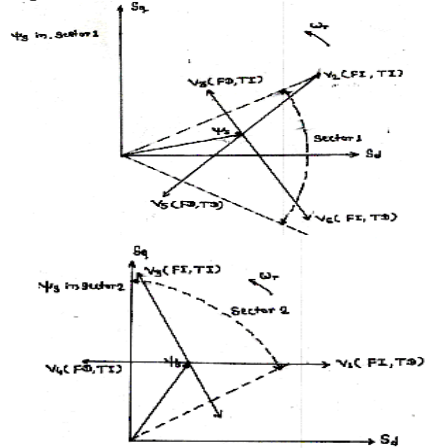

Fig. 1.9. Position of various stator flux-linkage space vector & selection of the optimum switching voltage vectors.

Where, FI – flux increases; FD – flux decreases, TI – torque increases;TD – torque decreases. Similarly, the stator flux linkage vector modulus is limited to a choice of increase or decrease. The position of flux & torque elaborating switching table on space diagram are shown in figure 1.9.

VII. IMPLEMENTATION OF DTC SCHEME IN MATLAB

The complete scheme is implemented in MATLAB environment using the advance library function of simulink. The various block diagrams are shown below. The complete DTC scheme block shows the interconnections between various subsystems of DTC. The fig. 2 shows the SVPWM based VSI fed induction motor drive. Space vector PWM generator is shown in fig. 2.1 whereas the subsystem for speed controller is shown in fig. 2.2.
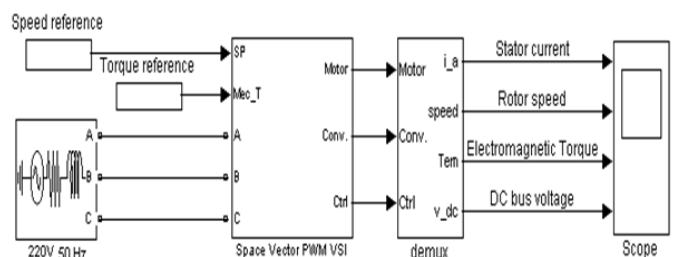

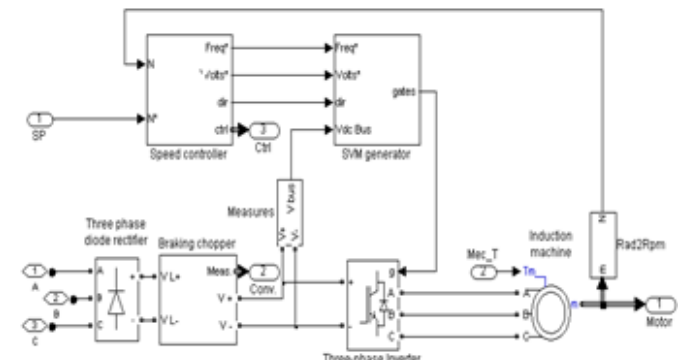Fig. 2. SVPWM based VSI fed induction motor drive.
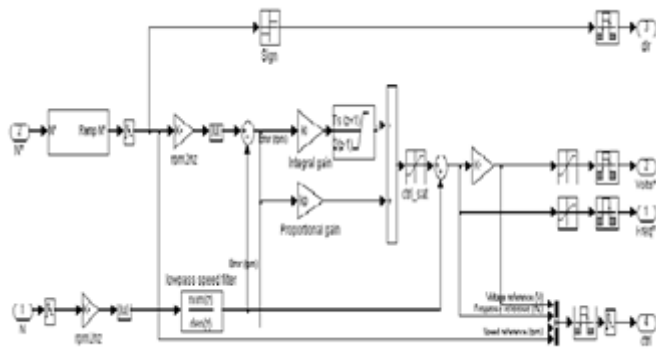

Fig. 2.1. Space vector PWM generator.

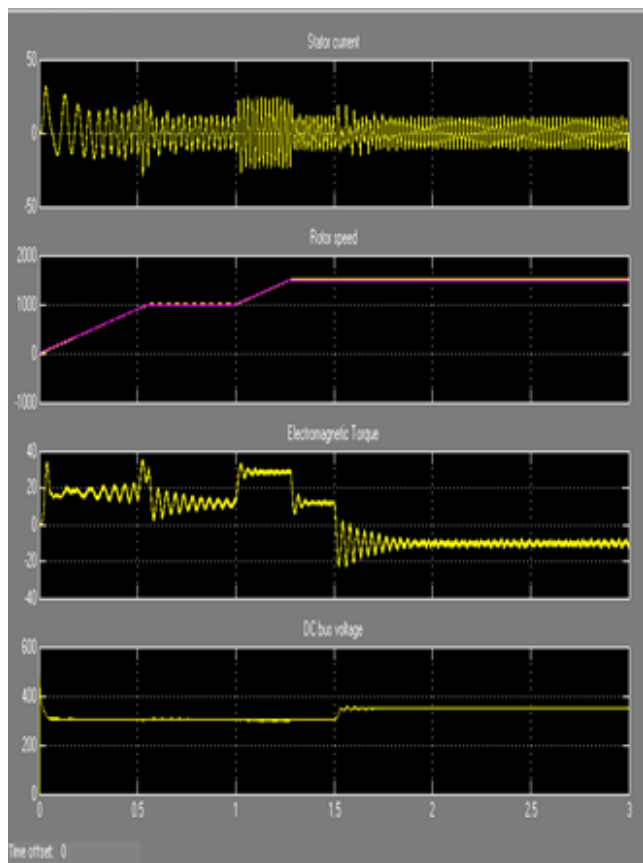Fig. 2.2. Speed controller.

VIII. RESULTS

Fig. 2.3. a) Stator current, b) Rotor speed, C) Electromagnetic torque and d) DC bus voltage.
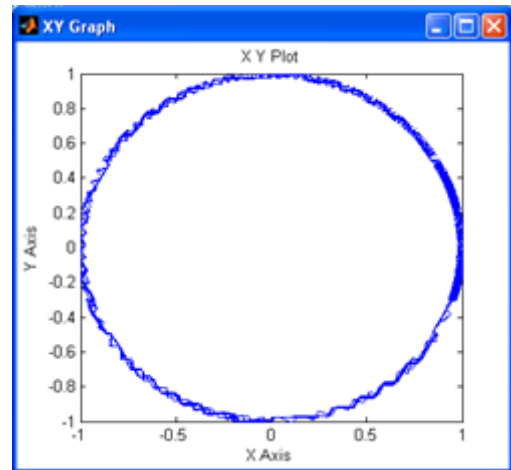

Fig. 2.4. Stator flux trajectory.

IX. CONCLUSION

The direct torque & flux control employs the concept of SVPWM along with full utilization of strength of active voltage vectors. The sequence of active/ zero vectors are impressed to the stator terminal of the motor depending on the torque controller demand. This control technique offers high dynamic response along with the sinusoidal PWM technique.

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