# Direct Torque Control Based on Space Vector Modulation with Adaptive Stator Flux Observer for Induction Motors

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## ABSTRACT

**This paper describes a combination of direct torque control (DTC) and space vector modulation (SVM) for an adjustable speed sensor less induction motor (IM) drive. The motor drive is supplied by a two-level SVPWM inverter. Using the IM model in the stator – axes reference frame with stator current and flux vectors components as state variables. In this paper, a conventional PI controller is designed accordingly for DTC-SVM system. Moreover, a robust full-order adaptive stator flux observer is designed for a speed sensor less DTC-SVM system and a new speed adaptive law is given. By designing the observer gain matrix based on state feedback control theory, the stability and robustness of the observer systems is ensured. Finally, the effectiveness and validity of the proposed control approach is verified by simulation results.**

**Keywords- DTC, Stator Flux Observer, Torque Ripple**

## I. INTRODUCTION

**D**IRECT TORQUE CONTROL (DTC) abandons the stator current control philosophy, characteristic of field oriented control (FOC) and achieves bang bang torque and flux control by directly modifying the stator voltage in accordance with the torque and flux errors. So, it presents a good tracking for both electromagnetic torque and stator flux [1]. DTC is characterized by fast dynamic response, structural simplicity, and strong robustness in the face of parameter uncertainties and perturbations.

One of the disadvantages of conventional DTC is high torque ripple [2]. Several techniques have been developed to reduce the torque ripple. One of them is duty ratio control method. In duty ratio control, a selected output voltage vector is applied for a portion of one sampling period, and a zero voltage vector is applied for the rest of the period. The pulse duration of output voltage vector can be determined by a fuzzy logic controller [3]. In [4], torque-ripple minimum condition during one sampling period is obtained from instantaneous torque variation equations. The pulse duration of output voltage vector is determined by the torque-ripple minimum condition. These improvements can greatly reduce the torque ripple, but they increase the complexity of DTC algorithm. An alternative method to reduce the ripples is based on space vector modulation (SVM) technique [5], [6].

Direct torque control based on space vector modulation (DTC-SVM) preserve DTC transient merits, furthermore, produce better quality steady-state performance in a wide speed range. At each cycle period, SVM technique is used to obtain the reference voltage space vector to exactly compensate the flux and torque errors. The torque ripple of DTC-SVM in low speed can be significantly improved.

In this paper, SVM-DTC technique with PI controller for induction machine drives is developed. Furthermore, a robust full-order speed adaptive stator flux observer is designed for a speed sensor less DTC-SVM system and a speed-adaptive law is given. The observer gain matrix, which is obtained by solving linear matrix inequality, can improve the robustness of the adaptive observer gain in [7]. The stability of the speed adaptive stator flux observer is also guaranteed by the gain matrix in very low speed. The proposed control algorithms are verified by extensive simulation results.

## II. DTC-SVM TECHNIQUE

### A. Model of Induction Motor

Under assumption of linearity of the magnetic circuit neglecting the iron loss, a three-phase IM model in a stationary axes reference with stator currents and flux are assumed as state variables, is expressed by

$$\ddot{i}_D = -\left(\frac{Rs}{\sigma Ls} + \frac{\Delta Rr}{\sigma Lr}\right) i_D - \omega_r i_Q + \frac{R_r \psi_D}{\sigma Ls Lr} + \frac{\psi_Q \omega_r}{\sigma Ls} + \frac{\mathcal{U}_D}{\sigma Ls} \quad (1)$$

$$\ddot{i}_Q = \left(\frac{Rs}{\sigma Ls} + \frac{\Delta Rr}{\sigma Lr}\right) i_Q + \omega_r i_D + \frac{R_r \psi_Q}{\sigma Ls Lr} - \frac{\psi_D \omega_r}{\sigma Ls} + \frac{\mathcal{U}_Q}{\sigma Ls} \quad (2)$$

$$\dot{\psi}_D = \mathcal{U}_D - R_s i_D \quad (3)$$

$$\dot{\psi}_Q = \mathcal{U}_Q - R_s i_Q \quad (4)$$

where, $\psi_D, \psi_Q, \mathcal{U}_D, \mathcal{U}_Q, i_D, i_Q$ are respectively the D Q axes whereof the stator flux, stator voltage and stator current vector component $\omega_m$ is the rotor electricalangular speed, $L_S, L_r, L_M$ are the stator, rotor, and magnetizing inductances, respectively, $\sigma = 1 -$

$(L_M^2/L_R L_S)$ and $R_S$,$R_r$, are the stator and rotor resistances, respectively.

The electromagnetic torque$T_e$ in the induction motor can be expressed as

$T_e = P_n\psi_s \times i_s = P_n(\psi_D i_Q - \psi_Q i_D)$ (5)

Where $P_n$ is the number of pole pairs.

**B. DTC-SVM Technique**

The DTC-SVM scheme is developed based on the IM torque and the stator flux modules as the system outputs is shown in fig.1.

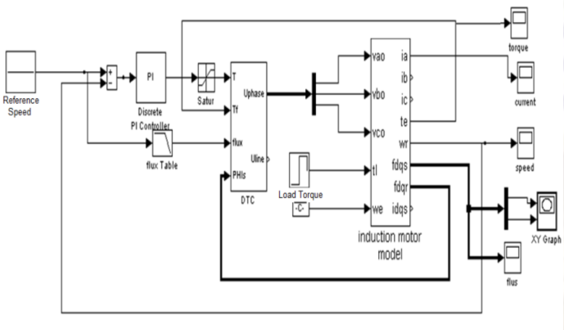


**Fig. 1 Block Diagram of DTC-SVM system**

The stator voltage components are defined as system control inputs and stator currents as measurable state variables.

Let the system output be

$$y_1 = T_e = \rho_n\left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}\right) \quad (6)$$

$$y_2 = |\psi_s|^2 = \psi_{ds}^2 + \psi_{qs}^2 \quad (7)$$

Define the controller objectives $e_1$ and $e_2$ as

$$e_1 = T_e - T_{eref} \quad (8)$$

$$e_2 = |\psi_s| - |\psi_{ref}| \quad (9)$$

Where $T_{eref}$,$\psi_{ref}$ are reference value of electromagnetic torqueand stator flux, respectively. The flux control loop and torque control are shown in fig.2

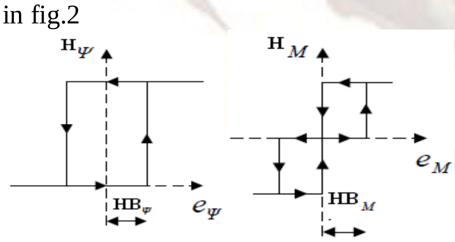


**Fig.2 Control Strategy of DTC**

**C. DTC-SVM Technique with PI Controller**

PI control is one of the earlier control strategies. It is applied to the D-axis and Q-axis rotor flux of the Induction motor obtained from the IM model equation of (1) – (4). This improvement can greatly reduce the torque ripple. The Block diagram of DTC-SVM with PI controller is shown in fig.3.

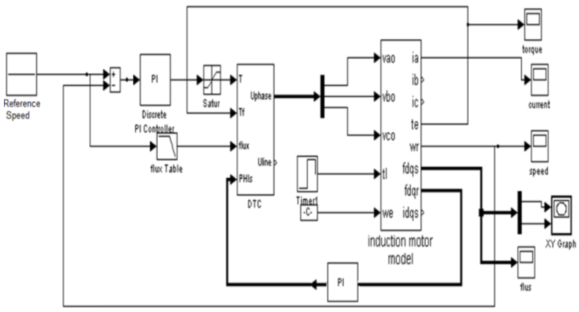


**Fig. 3DTC-SVM with PI controller**

## III. SPEED ADAPTIVE STATOR FLUX OBSERVER

### A. Speed Adaptive Stator Flux Observer

Using the IM model of (1)–(4), the speed adaptive stator fluxobserver is introduced:

$$\dot{x} = Ax + BU$$

$i_s = Cx$(10)

where

$\mathbf{x}=(i_D i_Q \psi_D \psi_Q)^T$, u =( $u_D u_Q)^T$

$\mathbf{i}_s=(i_D i_Q)^T$

$\mathbf{B}=[\frac{1}{\sigma Ls} II]^T \mathbf{C} =[I \quad 0]$ , $\mathbf{I}=\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}\mathbf{J}=\begin{bmatrix}0 & -1\\1 & 0\end{bmatrix}$

$\mathbf{A}=\mathbf{A}_0+\Delta\mathbf{A}_R + \omega_r\mathbf{A}\omega$

$$=\begin{bmatrix}-\left(\frac{Rso}{\sigma Ls}+\frac{Rro}{\sigma Lr}\right)I & \frac{Rso}{\sigma LsLr}I\\ -R_{s0}I & 0\end{bmatrix}+$$

$$\begin{bmatrix}-\left(\frac{\Delta Rs}{\sigma Ls}+\frac{\Delta Rr}{\sigma Lr}\right)I & \frac{\Delta Rso}{\sigma LsLr}I\\ -\Delta R_{s0}I & 0\end{bmatrix}+\omega_r\begin{bmatrix}J & \frac{1}{\sigma Ls}J\\ 0 & 0\end{bmatrix}$$

the uncertain parameters in matrix **A** are split in two parts; one corresponding to nominal or constant operation and the second unknown behavior.$R_{s0}$ and $R_{r0}$ are nominal value stator resistance and rotor resistance,$\Delta R_s$ and $\Delta R_r$ are stator resistance and rotor resistance uncertainties, respectively.

The state observer, which estimates the state current and the stator flux together, is given by the following equation:

$\frac{d\hat{x}}{dt}= (A_0+\Delta A_R+\hat{\omega}_r A_\omega)\hat{x}+Bu+H(\hat{i_s}-i_s)$(11)

Where $\hat{x}=(i_D i_Q \psi_D \psi_Q)^T$are estimated values of the state variable and **H** is the observer matrix.

Supposing state error is i.e., e=$\hat{x}$-$x$, so

$\frac{d}{dt}(e) =\frac{d}{dt}(\hat{x}) -\frac{d}{dt}(x)$

$= (A_0+HC+\Delta A_R+\omega_r A_\omega)e +\Delta\omega_r A_\omega\hat{x}$(12)

In order to derive the adaptive scheme, Lyapunov theorem is utilized. Now, let us define the following Lyapunov function:

$V = e^T e+(\hat{\omega}_r-\omega_r)^2/\lambda$ (13)

The time derivative of V is as follows:

$\frac{dv}{dt}=e^T[(A_0 +HC+\Delta A_R+\omega_r A\omega)^T$

$(A0 + HC + \Delta A_R+\omega_r A\omega)]e$

$+\Delta\omega_r(\hat{x}^T A_\omega^T e + e^T A\omega\hat{x})+\frac{2}{\lambda}(\hat{\omega}_r-\omega_r)\frac{d\hat{\omega}_r}{dt}$(14)

Let

$$\Delta\,\omega_r(\hat{x}^T A_\omega^T e + e^T A\omega\hat{x}) + \frac{2}{\lambda}(\hat{\omega}_r - \omega_r)\frac{d\hat{\omega}_r}{dt} = 0 \qquad (15)$$

If we select observer gain matrix **H** so that the validity of inequality

$$e^T[(A_0 + HC + \Delta A_R + \omega_r A\omega)^T + (A_0 + HC + \Delta A_R + \omega_r A\omega)]\,e < 0 \qquad (16)$$

can be guaranteed, the state observer is stable.
The adaptive scheme for speed estimation is given by

$$\hat{\omega}_r = \left(K_p + \frac{K_i}{P}\right)(\psi_s{}^T)\,J\,(\hat{i}_s - i_s) \qquad (17)$$

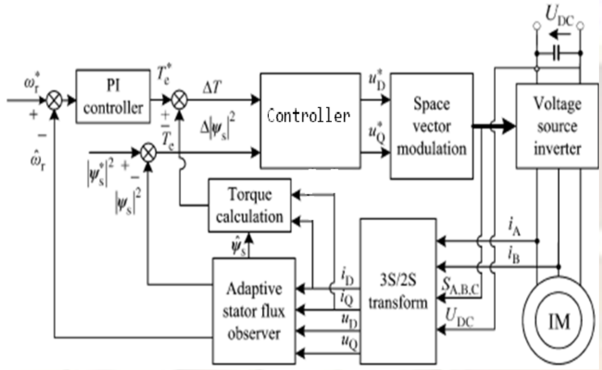


**Fig. 4 DTC-SVM with Adaptive Stator flux observer**

## B. Observer Gain Matrix Computation

Let's introduce a theorem about quadratic stability of uncertainty system before design the observer gain matrix.
Lemma: Uncertainty system

$$\dot{x}(t) = (A_0 + \Delta A(t))x(t), x(0) = x_0 \qquad (18)$$

is quadratic stable, if and only if $A_0$ is Stable and

$$\|F(sI - A_0)^{-1}E\|_\infty < 1 \qquad (19)$$

Where $A_0$ is nominal matrix, which is supposed to be Well Know $\Delta A = E\delta F$ is represent the un certainties on A due to unmodeled behavior or parameters drift ,E and F are the uncertainty structure matrices of the system, $\delta$ is uncertainty coefficient.
If $\Delta A_R$ is also written as $\Delta A_R = E\delta F$, so system (16) is quadratic stable,if and only if $A_0 + \omega_r A\omega + HC$ is stable and

$$\|F(sI - A_0 - \omega r A\omega - HC)^{-1}E\|_\infty < 1 \qquad (20)$$

Supposing K= HC quadratic stability problem of system (12) can be transformed to static state feedback $H_\infty$ control problem for the system

A State –Space realization of Fig.1 is as (21)

$$G(s) = \left[\begin{array}{c|cc} A_0 + \omega r A\omega & E & I \\ F & 0 & 0 \\ I & 0 & 0 \end{array}\right] \qquad (21)$$

As System(21), there will be a state feedback $H_\infty$ controller K, if and only if there are positive definite matrix X and W to make linear matrix inequality (22) is satisfied

$$\begin{bmatrix} AX + W(AX+W)^T & E & (FX)^T \\ E^T & -I & 0 \\ FX & 0 & -I \end{bmatrix} < 0 \qquad (22)$$

If $X^*$ and $W^*$is a feasible solution to linear matrix inequality (22),then u= $W^*(X^*)^{-1}x$is a state feedback$H_\infty$controller of system(21). So, K= $W^*(X^*)^{-1}$ .the observer gain matrix can be obtained from $H = KC^{-1}$

Table I
Parameters of IM

| | |
|---|---|
| Rated power $P_N$(kW) | 3 |
| Rated voltage $U_N$(V) | 380 |
| Rated current $I_N$(A) | 6.8 |
| Rated frequency $f$(Hz) | 50 |
| Magnetic pole pairs $p_n$ | 2 |
| Rated speed $n$(r/min) | 1420 |
| Stator inductance $L_s$(H) | 0.086 |
| Rotor inductance $L_r$(H) | 0.086 |
| Mutual inductance $L_m$(H) | 0.243 |
| Stator resistance $R_s$(Ω) | 1.635 |
| Rotor resistance $R_r$(Ω) | 1.9 |
| Stator flux linkage $\psi_s$(Wb) | 0.8 |

## IV. SIMULATIONS

To verify the DTC-SVM scheme without controller, with PI controller and with adaptive stator flux observer simulations are performed in this section. The block diagram of the proposed system is shown in Fig. 4. The parameters of the induction motor used in simulation results are as Table I.

### Case A: DTC without controller

The reference stator flux used is 0.8 Wb and the command speed value is 1420 rpm in both two systems. The speed and torque response curves of conventional DTC and proposed DTC-SVM are shown Fig. 6- Fig. 14. At startup, the system is unloaded, the load torque is changed to 2 Nm at t=0.3s, then the load torque is changed from 2 Nm to 1 Nm at t=0.6 s. The stator flux observer curves are shown in Figs. 8 and 9.
The torque ripple is calculated using the equation

$$T_{ripple}\,(\%) = \frac{T_{max} - T_{min}}{T_{ref}} * 100$$

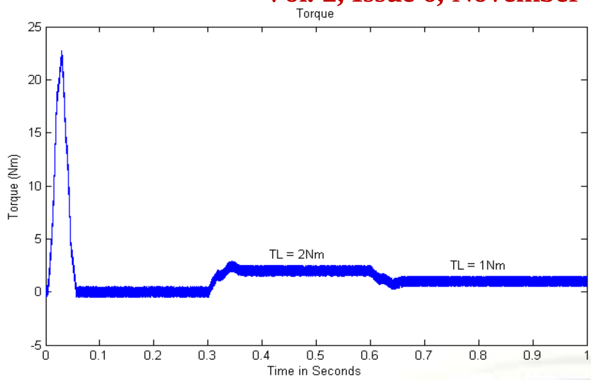


**Fig. 6Torque waveform**

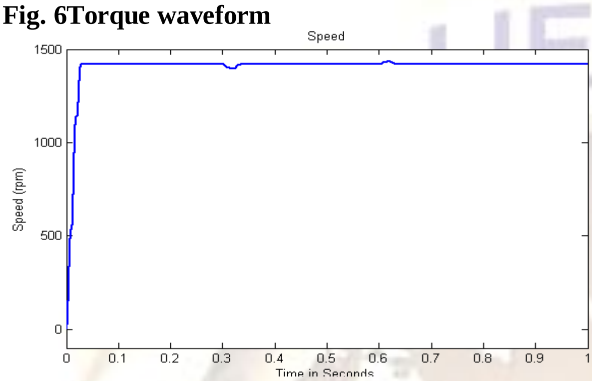


**Fig. 7Speed waveform**

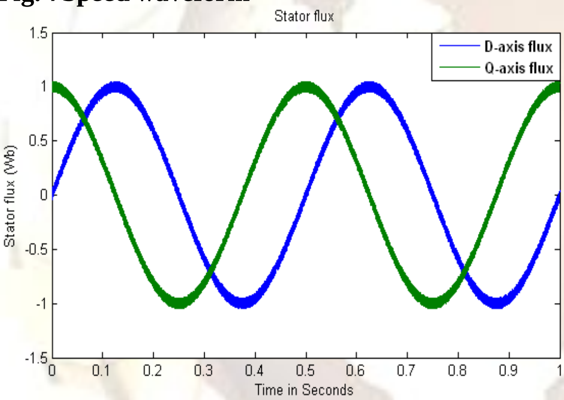


**Fig. 8Stator Flux waveforms**

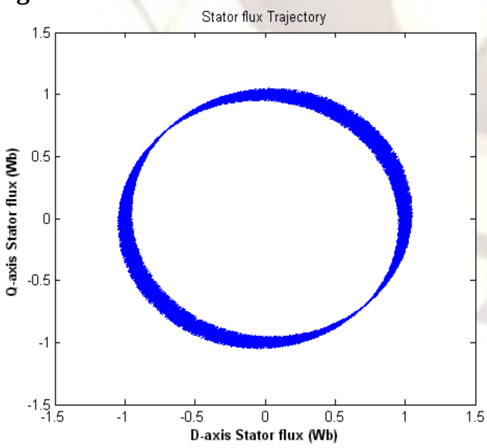


**Fig. 9Stator flux Trajectory**

***Case B: DTC with PI controller***

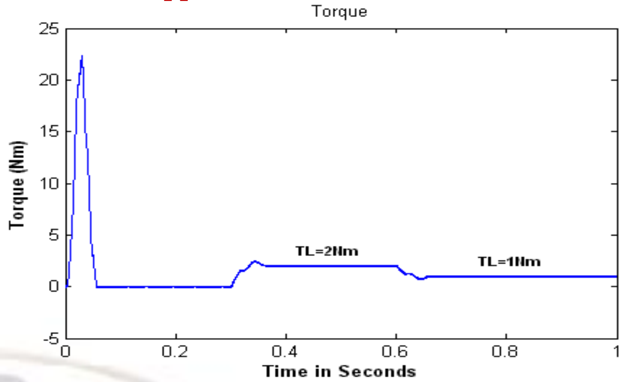


**Fig. 10Torque waveform**

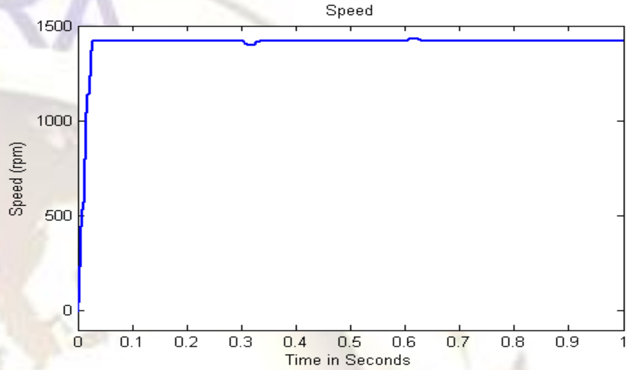


**Fig. 11Speed waveform**

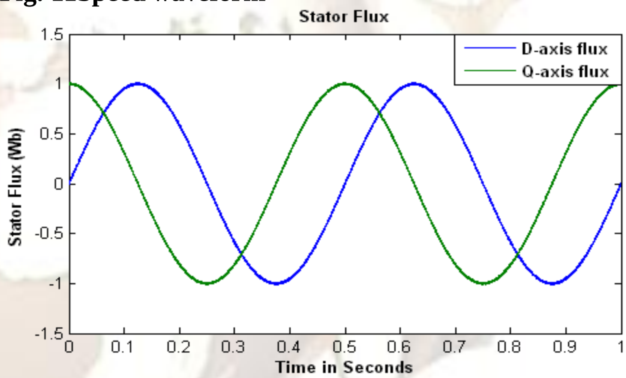


**Fig. 12Stator Flux waveforms**

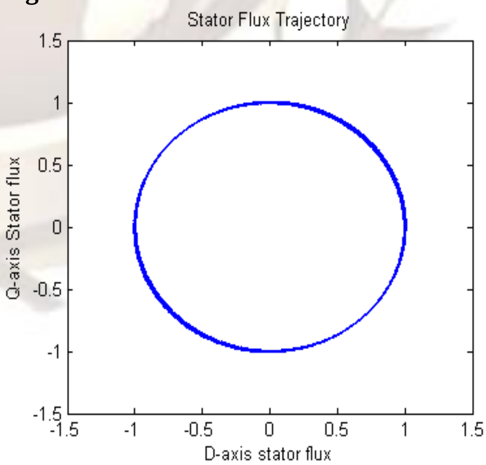


**Fig. 13Stator flux Trajectory**

***Case C: DTC with Stator Flux observer***

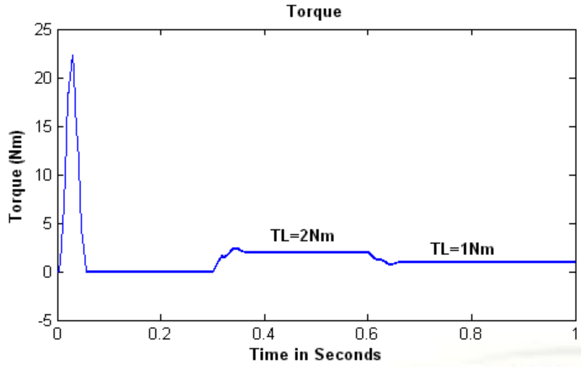


**Fig. 14Torque waveform**

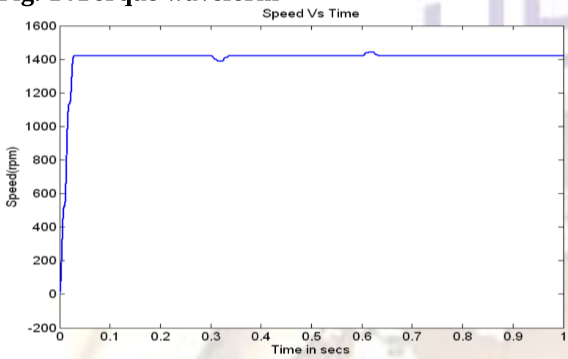


**Fig. 15Speed waveform**

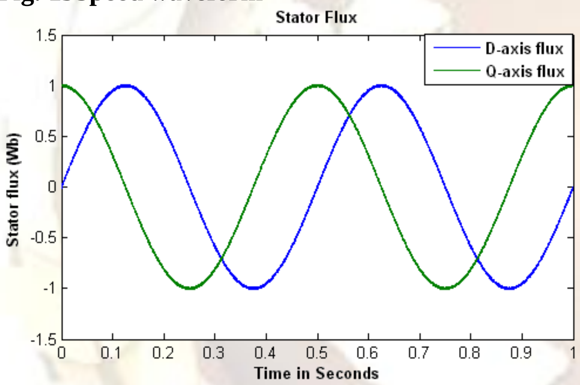


**Fig. 16Stator Flux waveforms**

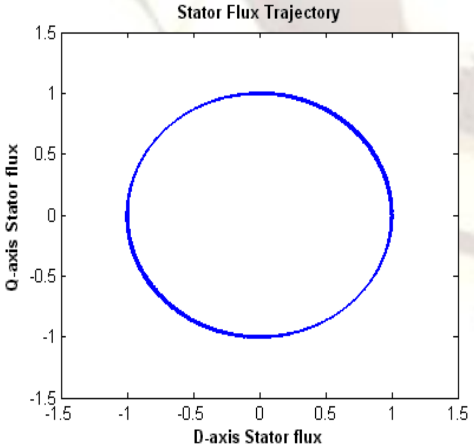


**Fig. 17Stator flux Trajectory**

Compared with conventional DTC, the DTC with PI controller has smaller torque ripple, furthermore the DTC with Stator flux observer has much smaller torque ripple. From Fig.17, it can be seen that the adaptive observer can estimate the stator flux well and truly. The torque ripple for all the three cases at different load torques is shown in Table II.

| Load Torque / Method | T=2Nm | T=4Nm | T=6Nm | T=8Nm | T=10Nm |
|---|---|---|---|---|---|
| **Conventional** | 50% | 25% | 16.6% | 12.5% | 10% |
| **Conventional with PI** | 6% | 3% | 2% | 1.5% | 1.2% |
| **Conventional with flux observer** | 5% | 2.5% | 1.66% | 1.25% | 1% |

## V.CONCLUSION

A novel DTC-SVM scheme has been developed for the IMdrive system, In this control method, a SVPWM inverter is used tofeed the motor, the stator voltage vector is obtained to fully compensate the stator flux and torque errors. Furthermore, a robustfull-order adaptive flux observer is designed for a speed sensor-less DTC-SVM system. The stator flux and speed are estimated synchronously. By designing the constant observer gain matrix, the robustness and based on state feedback stability of the observer systems is ensured. Therefore, the proposed sensor-less drive system is capable of steadily working in very low speed, has much smaller torque ripple and exhibits good dynamic and steady-state performance.

## REFERENCES

[1] I. Takahashi and T. Noguchi, “A new quick-response and high efficiency control strategy of an induction motor,” IEEE Trans. Ind. Appl.,vol. IA-22, no. 5, pp. 820–827, 1986.

[2] Y. S. Lai and J. H. Chen, “A new approach to direct torque control ofinduction motor drives for constant inverter switching frequency andtorque ripple reduction,” IEEE Trans. Energy Convers., vol. 16, no. 3,pp. 220–227, 2001.

[3] S. Mir, M. E. Elbuluk, and D. S. Zinger, “PI and fuzzy estimators for tuning the stator resistance in direct torque control of induction machines,” IEEE Trans. Power Electron., vol. 13, no. 2, pp. 279–287,1998.

[4] F. Bacha, R. Dhifaoui, and H. Buyse, “Real-time implementation ofdirect torque control of an induction machine by fuzzy logic controller,” in Proc. ICEMS, 2001, vol. 2, pp. 1244–1249.

[5] A. Arias, J. L. Romeral, and E. Aldabas, “Fuzzy logic direct torquecontrol,” in Proc.

IEEE ISIE, 2000, vol. 1, pp. 253–258.

[6] D. Seyoum, M. F. Rahman, and C. Grantham, “Simplified flux estimation for control application in induction machines,” in IEMDC’03,2003, vol. 2, pp. 691–695.

[7] G. Xi, H. Gao, and W. Xu et al., “A method to determine gain matrixof stator flux full order observer,” J. Cent. South Univ.(Science andTechnology),vol. 39, no.4, pp. 793–798, 2008.

[8] J. Soltani1, G. R. A. Markadeh, and N. R. Abjadi3 et al., “A new adaptive direct torque control (DTC) scheme based-on SVM for adjustable speed sensorless induction motor drive,” in ICEMS 2007, Seoul, Korea, Oct. 8–11, 2007, pp. 497–502.