Novel DTC-SVM for an Adjustable Speed Sensorless Induction Motor Drive

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ABSTRACT:

This paper presents, the direct torque control (DTC) based space vector modulation (SVM) for an adjustable speed sensorless induction motor (IM) drive. This proposed system will give a clear study about DTC and SVM and the motor drive is supplied by a two-level SVPWM inverter. Based on input-output feedback linearization control the inverter reference voltage is obtained, using the IM model in the stator D–Q axes reference frame with stator current and flux vectors components as state variables. Moreover, a robust full-order adaptive stator flux observer is designed for a speed sensorless DTC-SVM system and a new speed-adaptive law is given. By designing the observer gain matrix based on state feedback H∞ control theory, the stability and robustness of the observer systems is ensured. The speed adaptive stator flux observer stability guaranteed also by the gain matrix in very low speed. The experimental results are proved by simulation results.

I.INTRODUCTION:

Direct Torque Control (DTC) is a method that has emerged to become one possible alternative to the well-known Vector Control of Induction Motors. This method provides a good performance with a simpler structure and control diagram. Direct 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. 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. 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. In 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 an 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. 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 based on input-output linearization control scheme for induction machine drives is developed. Furthermore, a robust full-order speed adaptive stator flux observer is designed for a speed sensorless 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. The stability of the speed adaptive stator flux observer is also guaranteed by the gain matrix in very low speed.

II.PROPOSED SYSTEM DESCRIPTION:

1. Direct Torque Control: Direct Torque Control (DTC) is a method that has emerged to become one possible alternative to the well-known Vector Control of Induction Motors. This method provides a good performance with a simpler structure and control diagram. In DTC it is possible to control directly the stator flux and the torque by selecting the appropriate VSI state.
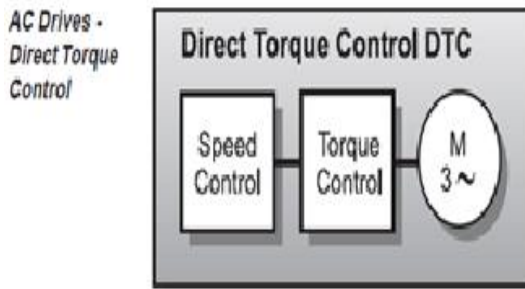
To achieve a high level of torque response and speed accuracy, a feedback device is required. This can be costly and also adds complexity to the traditional simple AC induction motor. Also, a modulator is used, which slows down communication between the incoming voltage and frequency signals and the need for the motor to respond to this changing signal. Although the motor is mechanically simple, the drive is electrically complex.

Controlling Variables: With the revolutionary DTC technology developed by ABB, field orientation is achieved without feedback using advanced motor theory to calculate the motor torque directly and without using modulation. The controlling variables are motor magnetizing flux and motor torque. With DTC there is no modulator and no requirement for a tachometer or position encoder to feed back the speed or position of the motor shaft.DTC uses the fastest digital signal processing hardware available and a more advanced mathematical understanding of how a motor works. The result is a drive with a torque response that is typically 10 times faster than any AC or DC drive. The dynamic speed accuracy of DTC drives will be 8 times better than any open loop AC drives and comparable to a DC drive that is using feedback. DTC produces the first "universal" drive with the capability to perform like either an AC or DC drive. The remaining sections in this guide highlight the features and advantages of DTC.

2. The Space Vector PWM Theory: The Space Vector PWM generation module accepts modulation index commands and generates the appropriate gate drive waveforms for each PWM cycle. This section describes the operation and configuration of the SVPWM module. A three-phase 2-level inverter with dc link configuration can have eight possible switching states, which generates output voltage of the inverter. Each inverter switching state generates a voltage Space Vector (V1 to V6 active vectors, V7 and V8 zero voltage vectors) in the Space Vector plane (Figure: space vector diagram). The magnitude of each active vector (V1to V6) is 2/3 Vdc (dc bus voltage).

The Space Vector PWM (SVPWM) module inputs modulation index commands (U_Alpha and U_Beta) which are orthogonal signals (Alpha and Beta) as shown in Figure 1. The vertical axis of Figure represents the normalized peak motor phase voltage (V/Vdc) and the horizontal axis represents the normalized modulation index (M).
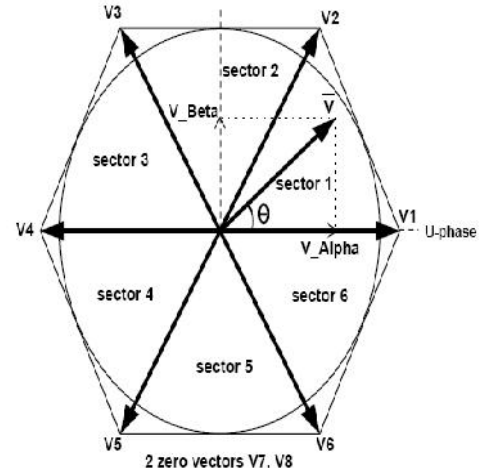

Fig 1: Space Vector Diagram

3. SVM PWM Technique: The Pulse Width modulation technique permits to obtain three phase system voltages, which can be applied to the controlled output. Space Vector Modulation (SVM) principle differs from other PWM processes in the fact that all three drive signals for the inverter will be created simultaneously. The implementation of SVM process in digital systems necessitates less operation time and also less program memory.

III. MODELING OF CASE STUDY:

1. DTC-SVM BASED ON INPUT-OUTPUT LINEARIZATION:

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 DQ – axes reference with stator currents and flux are assumed as state variables, is expressed by

$$i_D = -\left(\frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r}\right) i_D - \omega_r i_Q + \frac{R_r \psi_D}{\sigma L_s L_r} + \frac{\omega_r \psi_Q}{\sigma L_s} + \frac{u_D}{\sigma L_s} \quad (1)$$

$$i_Q = -\left(\frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r}\right) i_Q + \omega_r i_D + \frac{R_r \psi_Q}{\sigma L_s L_r} - \frac{\omega_r \psi_D}{\sigma L_s} + \frac{u_Q}{\sigma L_s} \quad (2)$$

$$\psi_D = u_D - R_s i_D \quad (3)$$

$$\psi_Q = u_Q - R_s i_Q \quad (4)$$

Where ψ_D, ψ_Q, u_D, u_Q, i_D, i_Q are respectively the **D-Q** axes of the stator flux, stator voltage and stator current vector components, **Wm** is the rotor electrical angular speed **Ls, Lr, Lm** are the stator, rotor, and magnetizing inductances, respectively, $\sigma = 1 - (L_m^2/L_s L_r)$ and R_s, R_r, are the stator and rotor resistances, respectively.

The electromagnetic torque in the induction motor can be expressed as,

$$T_e = p_n \boldsymbol{\psi}_s \times \boldsymbol{i}_s = p_n(\psi_D i_Q - \psi_Q i_D) \qquad (5)$$

Where **Pn** is the number of pole pairs.

B. DTC-SVM Based on I/O Linearization: The DTC-SVM scheme is developed based on the IM torque and the square of stator flux modulus as the system outputs;
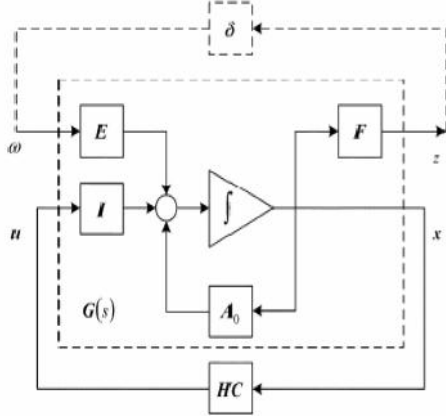

Fig 2: Standard H∞ design.

Stator voltage components defined as system control inputs and stator currents as measurable state variables. Let the system output be,

$$y_1 = T_e = p_n(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) \qquad (6)$$
$$y_2 = |\boldsymbol{\psi}_s|^2 = \psi_{ds}^2 + \psi_{qs}^2. \qquad (7)$$

Define the controller objectives e1 and e2 as,

$$e_1 = T_e - T_{eref} \qquad (8)$$
$$e_2 = |\boldsymbol{\psi}_s|^2 - |\boldsymbol{\psi}_{sref}|^2 \qquad (9)$$

Where $T_{eref}, \boldsymbol{\psi}_{sref}$, are reference value of electromagnetic torque and stator flux respectively. According to (1)–(5), the time derivative of E is as (10).

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \end{bmatrix} = \begin{bmatrix} g_1 \\ g_2 \end{bmatrix} + \boldsymbol{D} \begin{bmatrix} u_D^* \\ u_Q^* \end{bmatrix} \qquad (10)$$

Where,

$$g_1 = p_n \left[c(\psi_D i_Q - \psi_Q i_D) + \omega_m(\psi_D i_D + \psi_Q i_Q) - \frac{\omega_r}{\sigma L_s}|\boldsymbol{\psi}_s|^2 \right]$$
$$g_2 = -2R_s(\psi_D i_Q + \psi_Q i_D)$$
$$\boldsymbol{D} = \begin{bmatrix} \left(i_Q - \frac{\psi_Q}{\sigma L_s}\right) & -\left(i_D - \frac{\psi_D}{\sigma L_s}\right) \\ 2\psi_D & 2\psi_Q \end{bmatrix}$$
$$c = -\left(\frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r}\right).$$

According to the characteristic equation,

$$\boldsymbol{i}_s = (\boldsymbol{\psi}_s/\sigma L_s) - (L_m/\sigma L_s L_r)\boldsymbol{\psi}_r,$$

determinant of **D** is as follows:

$$\det(\boldsymbol{D}) = -\frac{4L_m}{\sigma L_r} p_n |\boldsymbol{\psi}_r| \cdot |\boldsymbol{\psi}_s| \cos(\boldsymbol{\psi}_r, \boldsymbol{\psi}_s). \qquad (11)$$

From (11), D is a non singular matrix since the inner product of stator flux vector and rotor flux vector cannot be physically zero.

Based on input-output feedback linearization, the following control inputs are introduced:

$$\begin{bmatrix} u_D^* \\ u_Q^* \end{bmatrix} = inv(\boldsymbol{D}) \begin{bmatrix} -g_1 + u_x \\ -g_2 + u_y \end{bmatrix} \qquad (12)$$

Where **u_x**, **u_y** are the auxiliary control inputs and are defined based on the pole placement concept of the linear control systems so that

$$u_x = c_1 c_1, \quad u_y = c_2 c_2 \qquad (13)$$

Where C1 and C2 are positive constants.

2. SPEED ADAPTIVE STATOR FLUX OBSERVER:

A. Speed Adaptive Stator Flux Observer: Using the IM model of (1)–(4), the speed adaptive stator flux observer is introduced:

$$\dot{\boldsymbol{x}} = \boldsymbol{Ax} + \boldsymbol{BU}$$
$$\boldsymbol{i}_s = \boldsymbol{Cx} \qquad (14)$$

Where,

$$\boldsymbol{x} = (i_D \ i_Q \ \psi_D \ \psi_Q)^T, \quad \boldsymbol{u} = (u_D \ u_Q)^T, \quad \boldsymbol{i}_s = (i_D \ i_Q)^T,$$
$$\boldsymbol{B} = \left[\frac{1}{\sigma L_s} \boldsymbol{I} \ \boldsymbol{I}\right]^T, \quad \boldsymbol{C} = [\boldsymbol{I} \ \boldsymbol{0}], \quad \boldsymbol{I} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad \boldsymbol{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix},$$
$$\boldsymbol{A} = \boldsymbol{A}_0 + \Delta \boldsymbol{A}_R + \omega_r \boldsymbol{A}_\omega$$
$$= \begin{bmatrix} \left(\frac{R_{s0}}{\sigma L_s} + \frac{R_{r0}}{\sigma L_r}\right)\boldsymbol{I} & \frac{R_{r0}}{\sigma L_s L_r}\boldsymbol{I} \\ R_{s0}\boldsymbol{I} & \boldsymbol{0} \end{bmatrix}$$
$$+ \begin{bmatrix} \left(\frac{\Delta R_s}{\sigma L_s} + \frac{\Delta R_r}{\sigma L_r}\right)\boldsymbol{I} & \frac{\Delta R_r}{\sigma L_s L_r}\boldsymbol{I} \\ -\Delta R_s\boldsymbol{I} & \boldsymbol{0} \end{bmatrix} + \omega_r \begin{bmatrix} \boldsymbol{J} & -\frac{1}{\sigma L_s}\boldsymbol{J} \\ \boldsymbol{0} & \boldsymbol{0} \end{bmatrix}$$

The uncertain parameters in matrix **A** are split in two parts; one corresponding to nominal or constant operation and the second to unknown behaviour. R_{s0} and R_{r0} are nominal value of stator resistance and rotor resistance, ΔR_s and ΔR_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:

$$\frac{d\hat{\boldsymbol{x}}}{dt} = (\boldsymbol{A}_0 + \Delta \boldsymbol{A}_R + \hat{\omega}_R \boldsymbol{A}_\omega)\hat{\boldsymbol{x}} + \boldsymbol{Bu} + \boldsymbol{H}(\hat{\boldsymbol{i}}_s - \boldsymbol{i}_s) \qquad (15)$$

Where $\hat{\boldsymbol{x}} = (\hat{i}_D \ \hat{i}_Q \ \hat{\psi}_D \ \hat{\psi}_Q)^T$ estimated values of the state variable and H are is the observer gain matrix

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

$$\frac{\mathrm{d}}{\mathrm{d}t}(e) = \frac{\mathrm{d}}{\mathrm{d}t}(\hat{x}) - \frac{\mathrm{d}}{\mathrm{d}t}(x)$$
$$= (A_0 + HC + \Delta A_{\mathrm{R}} + \omega_{\mathrm{r}} A_\omega)e + \Delta\omega_{\mathrm{r}} A_\omega \hat{x}. \quad (16)$$

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

$$V = e^{\mathrm{T}} e + (\hat{\omega}_{\mathrm{r}} - \omega_{\mathrm{r}})^2/\lambda. \quad (17)$$

The time derivative of **V** is as follows,

$$\frac{\mathrm{d}V}{\mathrm{d}t} = e^{\mathrm{T}} \left[(A_0 + HC + \Delta A_{\mathrm{R}} + \omega_{\mathrm{r}} A_\omega)^{\mathrm{T}} \right.$$
$$+ (A_0 + HC + \Delta A_{\mathrm{R}} + \omega_{\mathrm{r}} A_\omega) \right] e$$
$$+ \Delta\omega_{\mathrm{r}} \left(\hat{x}^{\mathrm{T}} A_\omega^{\mathrm{T}} e + e^{\mathrm{T}} A_\omega \hat{x} \right) + \frac{2}{\lambda}(\hat{\omega}_{\mathrm{r}} - \omega_{\mathrm{r}})\frac{\mathrm{d}\hat{\omega}_{\mathrm{r}}}{\mathrm{d}t}. \quad (18)$$

Let,

$$\Delta\omega_{\mathrm{r}} \left(\hat{x}^{\mathrm{T}} A_\omega^{\mathrm{T}} e + e^{\mathrm{T}} A_\omega \hat{x} \right) + \frac{2}{\lambda}\Delta\omega_{\mathrm{r}} \frac{\mathrm{d}\hat{\omega}_{\mathrm{r}}}{\mathrm{d}t} = 0 \quad (19)$$

if we select observer gain matrix H so that the validity of the inequality,

$$e^{\mathrm{T}} \left[(A_0 + HC + \Delta A_{\mathrm{R}} + \omega_{\mathrm{r}} A_\omega)^{\mathrm{T}} \right.$$
$$+ (A_0 + HC + \Delta A_{\mathrm{R}} + \omega_{\mathrm{r}} A_\omega) \right] e < 0 \quad (20)$$

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

$$\hat{\omega}_{\mathrm{r}} = \left(K_{\mathrm{P}} + \frac{K_{\mathrm{i}}}{p} \right) \left(\hat{\psi}_{\mathrm{s}}^{\mathrm{T}} \right) J(\hat{i}_{\mathrm{s}} - i_{\mathrm{s}}). \quad (21)$$
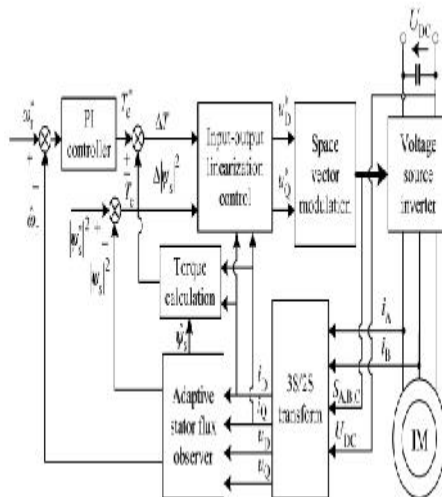

Fig 3: The block diagram of the DTC-SVM system

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

$$\dot{x}(t) = (A_0 + \Delta A(t)) x(t), \quad x(0) = x_0 \quad (22)$$

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

$$\|F(sI - A_0)^{-1} E\|_\infty < 1 \quad (23)$$

Where A_0 is nominal matrix, which is supposed to be well known, $\Delta A = E\delta F$ is represent the uncertainties on A due to un modeled behavior or parameter drift, E and F are the uncertainty structure matrices of the system, δ is uncertainty coefficient.

If ΔA_{R} is also written as $\Delta A_{\mathrm{R}} = E\delta F$, so system (16) is quadratic stable, if and only if $A_0 + \omega_{\mathrm{r}} A_\omega + HC$ is stable and

$$\|F(sI - A_0 - \omega_{\mathrm{r}} A_\omega - HC)^{-1} E\|_\infty < 1. \quad (24)$$

Supposing $K = HC$, quadratic stability problem of system (16) can be transformed to static state feedback H_∞ control problem for the system as Fig. 2.

A state-space realization of Fig. 2 is as

$$G(s) = \left[\begin{array}{c|cc} A_0 + \omega_{\mathrm{r}} A_\omega & E & I \\ \hline F & 0 & 0 \\ I & 0 & 0 \end{array} \right]. \quad (25)$$

As system (25), there will be a state feedback **H∞** controller **K**, if and only if there are positive definite matrix **X** and **W** to make linear matrix inequality (26) is satisfied

$$\left[\begin{array}{ccc} AX + W + (AX + W)^{\mathrm{T}} & E & (FX)^{\mathrm{T}} \\ E^{\mathrm{T}} & -I & 0 \\ FX & 0 & -I \end{array} \right] < 0, \quad (26)$$

If X^* and W^* is a feasible solution to linear matrix inequality (26), then $u = W^*(X^*)^{-1} x$ is a state feedback H_∞ controller of system (25). So, $K = W^*(X^*)^{-1}$. The observer gain matrix can be obtained from $H = KC^{-1}$.

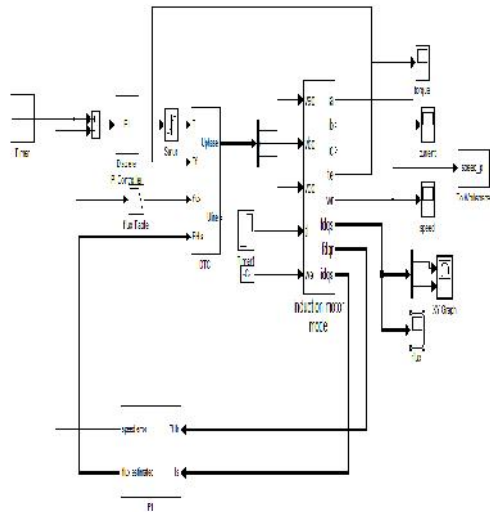## IV. SIMULATION CIRCUIT:

Fig 4: Simulation circuit of proposed DTC-SVM
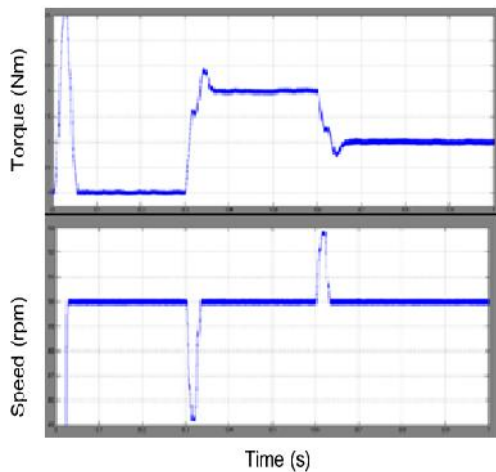
V. SIMULATION RESULTS:

Fig 5: Speed and Torque curves of proposed DTC-SVM technique
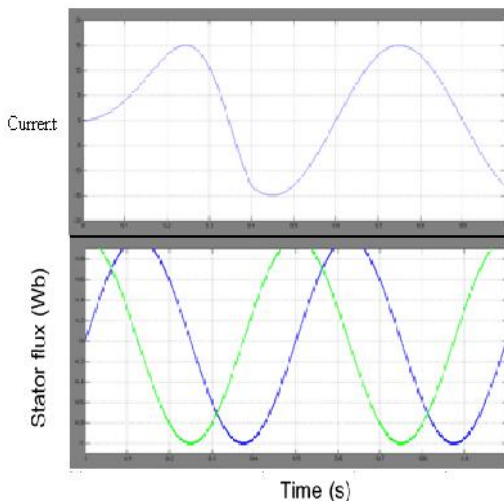

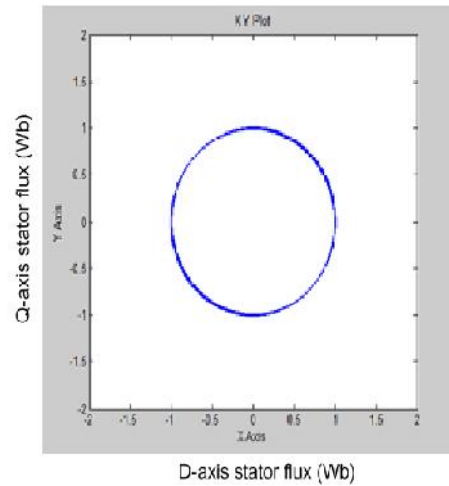Fig 6: Current and D-Q axes stator flux curve

Fig 7: Stator flux trajectory curve

VI. CONCLUSION:

A novel DTC-SVM scheme has been developed for the IM drive system, which is on the basis of input-output linearization control. In this control method, a SVPWM inverter is used to feed the motor, the stator voltage vector is obtained to fully compensate the stator flux and torque errors. Furthermore, a robust full-order adaptive flux observer is designed for a speed sensorless DTC-SVM system. The stator flux and speed are estimated synchronously. By designing the constant observer gain matrix based on state feedback control theory, the robustness and stability of the observer systems is ensured. Therefore, the pro- posed sensorless drive system is capable of steadily working in very low speed, has much smaller torque ripple and exhibits good dynamic and steady-state performance.

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