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Advanced Technique to Improve Dynamic Response of a Direct Torque Controlled Induction Motor

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Abstract- Direct torque control based on space vector modulation (SVM-DTC) preserve DTC transient merits, furthermore, produce better quality steady-state performance in a wide speed range. The SVM-DTC system based on input-output linearization technique for induction machine drives is developed in this paper. A sliding-mode observer for estimating flux is introduced. The observer is inherently sensor less because they do not employ the rotor speed adaptation, and thus they are insensitive to speed estimation errors. Moreover, the observer is extremely robust. The simulations of conventional DTC and the proposed control topologies are given and discussed. It is concluded that the proposed control topology outperforms the conventional DTC in reducing torque ripple and parameter robust.

Index Terms- Direct torque control , Sliding-Mode observer, Input-output Linearization.

I. Introduction

In high-performance variable-speed drive applications for induction machines, there are two most popular control strategies: field-oriented control (FOC) and direct torque control (DTC) [1,2]. Both of them can decouple the interaction between flux and torque control, and provide good torque response in steady state and transient operation conditions.

Unlike field-oriented control, direct torque control does not require coordinate transformation and any current regulator. It controls flux and torque directly based on their instantaneous errors [3]. In spite of its simplicity, direct torque control is capable of generating fast torque response [4]. In addition, direct torque control minimizes the use of machine parameters [5], so it is very little sensible to the parameters variation.

One of the disadvantages of conventional DTC is high torque ripple [6]. 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 [7]. In [8], 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 [9,10]. At each cycle period, a preview technique is used to obtain the voltage space vector required to exactly compensate the flux and torque errors. The required voltage space vector can be synthesized using SVM technique. The torque ripple for this SVM-DTC is significantly improved.

An approach for conventional DTC flux estimation is based on the voltage model integrators. The pure integrator has the following drawbacks. 1) input dc offset leads the output into saturation limit; 2) initial condition error produces a constant output dc offset; and 3) it is very sensitive to stator-resistance identification, especially at low speeds. Usually, adaptive observers employ the time-variable full order IM model to estimate the flux. At least one equation of the model contains a speed-dependent term, and the observer must always be speed adaptive. In most cases, the rotor speed calculation is the last step of the estimation process. Thus, the estimated speed is always affected by cumulative errors, noises, and time delays. This in accurate speed estimation is feed back to the adaptive flux observer and then the accuracy of flux and speed estimator may progressively worsen. Undesirable effects, such as limit cycles, higher noise sensitivity, or delays may occur and deteriorate the system overall performances, especially at very low stator frequencies, where the fundamental excitation is low. A solution for this is to use non adaptive observers. A distinct approach for sensor less flux estimation is based on full-order sliding-mode observers (SMOs). The sliding mode control theory presents promising features: disturbances rejection, strong robustness to parameter deviations, system order reduction [11]. Solutions using speed-adaptive SMOs are proposed in [12, 13]. These observers use sliding mode surfaces that combine the stator-current errors within the flux estimation. They are speed adaptive, with the aforementioned disadvantages. Accurate model parameters are required, especially in low-speed operation; therefore, online parameter identification is employed.

In this paper, SVM-DTC scheme based on input output linearization technique for induction machine drives is developed. Furthermore, a sliding-mode observer is used to estimate flux is introduced. The observer is inherently sensor less because it does not employ the rotor speed adaptation, and thus they are insensitive to speed estimation errors. Moreover, the observer is extremely robust. Simulation results with a sensor less direct-torque-controlled (DTC) IM drive using the observer prove the estimation accuracy, robustness, and high-dynamic performance in wide speed range. It is shown that the observer is able to sustain accurate very low-speed operation.

The remainder of this paper is organized as follows. The proposed SVM-DTC principle based on input-output linearization technique is described in Section II. In Section III, a sliding-mode observer for estimating flux is introduced. Simulation results of the proposed scheme are given and discussed in Section IV. Finally, conclusions are summarized in Section V

II. SVM-DTC Based on Input-output Linearization

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

$i_D = -[1/\alpha(R_s/L_s+R_r/ L_r)]\, i_D - \omega_m.i_Q+[R_r/(\alpha L_sL_r)].\Psi_D + [\omega_m/ \alpha L_s].\ \Psi_Q+ [1/ \alpha L_s].u_D$ (1)

$i_Q=-[1/\alpha(R_s/L_s+R_r/L_{ars})]\, i_Q +\omega_m.i_D+[R_r/(\alpha L_sL_r)].\Psi_Q - [\omega_m/ \alpha L_s].\ \Psi_D+[1/ \alpha L_s].u_Q$ (2)

$$\Psi_D= u_D- R_s.i_D \quad (3)$$
$$\Psi_Q= u_Q- R_s.i_Q \quad (4)$$

where $\Psi_D, \Psi_Q, u_D, u_Q, i_D, i_Q$ are respectively the d-q axes of the stator flux, stator voltage and stator current vectorcomponents, $\omega_m$is the rotor electrical angular speed, L_s, L_r, L_m are the stator, rotor, and magnetizing inductances, respectively, $\alpha=1-(L_m^2/L_sL_r)$and R_s, $R_r$are the stator and rotor resistances, respectively.

Also, the motor mechanical equation is

$$T_o=T_L+B\omega+J.\frac{d\omega}{dt} \quad (5)$$

where, ω is the rotor mechanical angular speed, T_L is the motor load torque, J is moment of inertia, B is factor of friction coefficient and T_e is the motor generated torque which is defined by:

$T_e = p_n\Psi_s * \boldsymbol{i}_s = p_n\ (\Psi_D i_Q - \Psi_Q i_D)$ (6)

where, p_n is the number of pole pairs.

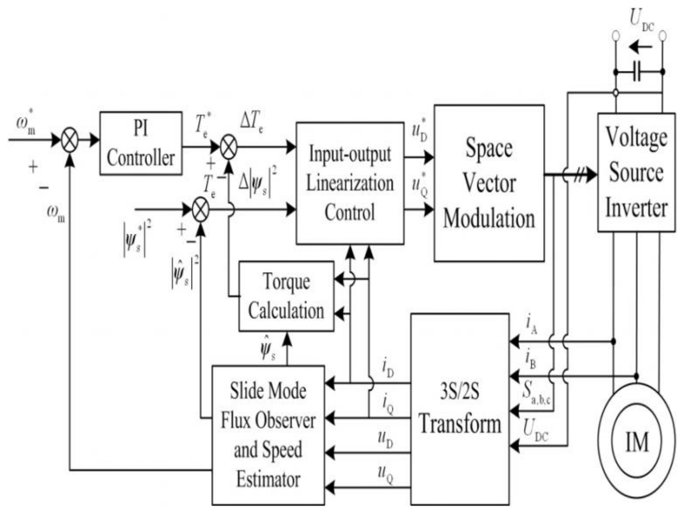

Fig 1: The block diagram of the DTC-SVM system

Unlike field-oriented control, direct torque control does not require coordinate transformation and any current regulator. It controls flux and torque directly based on their instantaneous errors. In spite of its simplicity, direct torque control is capable of generating fast torque response. In addition, direct torque control minimizes the use of machine parameters, so it is very little sensible to the parameters variation. However, there is only one voltage vector can be selected to minimizes the torque error and flux error in one sampling period and normal voltage source inverter can only provide six voltage vector. So it is impossible to minimizes the torque error and flux error. The SVM principle based on the switching between two adjacent active vectors and a zero vector during one switching period can synthesize arbitrary voltage vector, which can overcome the drawback of conventional DTC. The proposed DTC-SVM system based on feedback linearization is illustrated in fig.1.

The DTC-SVM scheme is developed based on the IM torque and the square of stator flux modulus as the system outputs; stator voltage components defined as system control inputs and stator currents as measurable state variables.

Define the controller objectives e_1 and e_2 as

$$e_1 = T_o - T_{oref} \quad (7)$$

$$e_2 = |\Psi_s^2| - |\Psi_{sref}^2| \quad (8)$$

From (1-6),

$$\overline{e_1} = \mathrm{d}\frac{\mathrm{To}}{\mathrm{dt}}$$
$$=p_n(\overline{\Psi_D}.i_Q+ \Psi_D.\overline{i_Q} - \overline{\Psi_Q}.i_D - \Psi_Q.\overline{i_D})$$
$$=p_n[\ c(\Psi_D.i_Q- \Psi_Q.i_D) + \omega_m(\Psi_D.i_D+ \Psi_Q.i_Q) - (\omega_r/\alpha L_s)\ |\Psi_s^2| + (\ i_Q- \Psi_Q/ \alpha L_s)\ u_D^* -(i_Q- \Psi_D/ \alpha L_s)\ u_Q^*] \quad (9)$$

$$\overline{e2} = \frac{d|\Psi_s^2|}{\mathrm{dt}} = \frac{\mathrm{d}(\Psi_D^2 + \Psi_Q^2)}{\mathrm{dt}}$$
$$= 2(\Psi_D.u_D^*+ \Psi_Q.u_Q^*) -2R_s\ (\Psi_D.i_Q+ \Psi_Q.i_D) \quad (10)$$

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Equations (9) and (10) in the form is

$$\begin{pmatrix} \overline{e_1} \\ e2 \end{pmatrix} = \begin{pmatrix} g1 \\ g2 \end{pmatrix} + D\begin{pmatrix} u_D* \\ u_Q* \end{pmatrix} \quad (11)$$

where,

$$g1 = p_n[c(\Psi_D.i_Q - \Psi_Q.i_D) + \omega_m(\Psi_D.i_D + \Psi_Q.i_Q)$$

$$- (\omega_r/\alpha L_s) \mid \Psi_s^2 \mid]$$

$$g2 = 2R_s(\Psi_D.i_Q + \Psi_Q.i_D)$$

$$D = \begin{bmatrix} (i_Q - \Psi_Q/\alpha Ls) & -(i_D - \Psi_D/\alpha Ls) \\ 2\Psi_D & 2\Psi_Q \end{bmatrix}$$

Using the IM model,

$$i_s = (\Psi_s/\alpha L_s) - (L_m/\alpha L_s L_r)\Psi_r \quad (12)$$

Linking (9-12),

$$\det(D) = -(4L_m/\alpha L_r)\, p_n\, (\Psi_d\Psi_D - \Psi_q\Psi_Q)$$

$$= -(4L_m/\alpha L_r).p_n(\Psi_r^T.\Psi_S) \quad (13)$$

$$= -(4L_m/\alpha L_r).p_n \mid \Psi_r \| \Psi_s \mid . \mathrm{Cos}\,(\Psi_r, \Psi_s)$$

From (13), ***D*** is a nonsingular matrix since the inner product of stator flux vector and rotor flux vector can not be physically zero. Based on input-output feedback linearizing, the following control inputs are introduced:

$$\begin{pmatrix} u_D^* \\ u_Q^* \end{pmatrix} = inv(D)\begin{pmatrix} -g_1 + u_x \\ -g_2 + u_y \end{pmatrix} (14)$$

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

$$u_x = -c_1.e_1, u_y = -c_2.e_2 \ (15)$$

Where c_1 and c_2 are positive constants.

The SVM unit receives the D-Q components of thereference voltage vector u_D* and u_Q*in a stator flux reference frame as inputs and generates the inverter's command signals.The reference voltage vector uref=u_D*+j.u_Q*derived from (14) can be produced by adding two adjacent active vectors$\mathbf{u_k}(u_k,\alpha_k)$ and $\mathbf{u_{k+1}}(u_{k+1},\alpha_{k+1})$,($\alpha_{k+1}=\alpha_k+\pi/3$)and, if necessary, a zero vector $\boldsymbol{u}_0$(000) or $\boldsymbol{u}_7$(111), which is illustrated in fig. 2.

The duty cycles t_1 and t_2 for each active vector are the solutions of the complex equation.

$$t_1 = \sqrt{3}.{}^{T}/_{U_{DC}}.|Uref|.\sin(\tfrac{\pi}{3} - \gamma) (16)$$

$$t_2 = \sqrt{3}.{}^{T}/_{U_{DC}}.|Uref|.\sin\gamma \quad (17)$$

where, $U_{DC}$is the dc-link voltage.

The duty cycle for the zero vectors is the remaining time inside the switching period T.

$$t_0 = T - t_1 - t_2 (18)$$

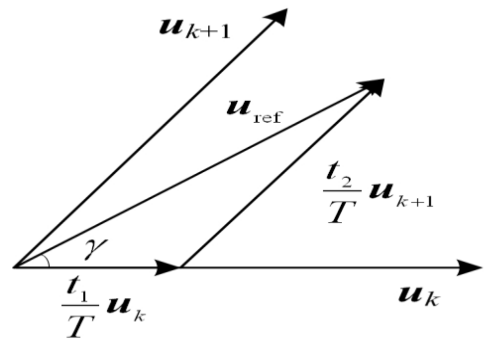

Fig.2 synthetically reference voltage vectors

The sequence guarantees that each transistor inside the inverter switches once and only once during the SVM switching period. A strict control of the switching frequency can be achieved by this approach. Fig.3 shows the command signals for the inverter when the vectors $\boldsymbol{u}_1$(100) or $\boldsymbol{u}_2$(110)and zero vectors $\boldsymbol{u}_0$(000) or $\boldsymbol{u}_7$(111) are applied.

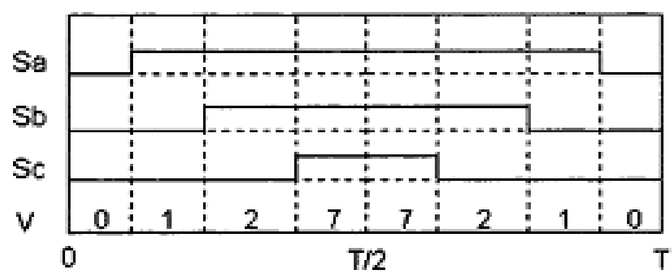

Fig.3 SVM voltage vector timing

III. SLIDING-MODE STATOR FLUX OBSERVER

The IM state model with stator-flux $\boldsymbol{\psi}_s$ and rotor-flux $\boldsymbol{\psi}_r$as state variables, in arbitrary reference frame rotating with angular speed ω_e is given by

$$\frac{d\Psi_s}{dt} = u_S - \left[\frac{1}{\alpha T_s} + j.\omega_0\right]\Psi_s + \frac{L_m}{\alpha T_s L_r}.\Psi_r (19)$$

$$\frac{d\Psi_r}{dt} = \frac{L_m}{\alpha T_r L_S}.\Psi_s + [j\left(\omega_0 - \omega_m\right) - \frac{1}{\alpha T_r}]\Psi_r \quad (20)$$

Where, $T_s = L_s/R_s$, $T_r = L_r/R_r$.

A. *SMO for Flux Estimation*

The full-order SMO for flux estimation is shown in Fig. 4, where the basic SMO solution has $k_{1I} = 0$. It is a sensor less observer that does not employ speed adaptation, and therefore, it is insensitive to speed estimation errors. This quality is extremely important at very low speeds and during fast transients, where the speed estimation tends to be poor. Moreover, the SMO technique helps to increase the overall robustness. In order to ease the implementation, to improve the estimation accuracy, and to avoid speed adaptation, the SMO is constructed using: 1) stator model in stator reference ($\omega_e = 0$, without superscript), replacing $\boldsymbol{\psi}_r$ from (12) in (19) and 2) rotor model in rotor-flux reference ($\omega_e = \omega_r$, with superscript "r").

Therefore

$$\frac{d\Psi_s{}^{\wedge}}{dt} = -R_s i_s + u_s + k_1 . sgn(i_s - \hat{i_s}) \quad (21)$$

$$\frac{d\Psi_r^{r\wedge}}{dt} = \frac{L_m}{\alpha T_r L_s} . \Psi_s{}^{\wedge} . e^{j\theta_r^-} - [j(\omega_r - \omega_m) + \frac{1}{\alpha T_s}]\Psi_r^{r\wedge} + k_2 . sgn(i_s - \hat{i_s}) . e^{j\theta_r^-} (22)$$

$$\hat{i_s} = \frac{1}{\alpha L_s} . \Psi_s{}^{\wedge} - \frac{L_m}{\alpha L_s L_r} . \Psi_r^{r\wedge} . e^{j\theta_r^-} (23)$$

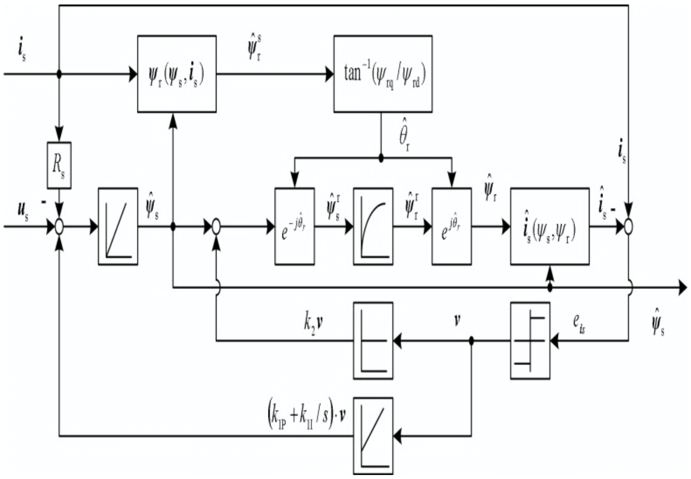

Fig.4 SMO for flux estimation

where, ω_r is the rotor-flux speed, k_1, k_2 are the observer gains, and "^" marks estimated variables or parameters.

Apparently, (22) employs the speed. In fact, there is no need, neither for ω_m, nor for ω_r, since in rotor-flux reference, the imaginary component of (22) is zero and its real component is

$$\frac{d\Psi_{rd}^{r\wedge}}{dt} = \frac{L_m}{\alpha T_r L_s} . \Psi_{sd}^{r\wedge} - \frac{1}{\alpha T_r}\Psi_{rd}^{r\wedge} + \mathrm{Re}\,(k_2 . sgn(i_s - \hat{i_s}) . e^{j\theta_r^-}) \quad (24)$$

The coordinate transformations require the angle

$$\hat{\theta}_r = \tan^{-1}(\Psi_{rq}{}^{\wedge}/\Psi_{rd}{}^{\wedge})$$

where ${}_r\Psi_r{}^{\wedge}$ in stator reference is

$$\Psi_r{}^{\wedge} = \frac{1}{L_m}(L_r . \Psi_s{}^{\wedge} - \alpha L_s L_r i_s) \quad (25)$$

An SMO gain with rotor-speed-dependent imaginary Components may be used

$K=[k_1 \quad k_2]^T=[k_{1r} + k_{1i}/s \quad k_{2r} + j . k_{2i} . \omega_m](26)$

where k_{1r}, k_{1i}, k_{2r}, k_{2i} are constants determined in simulation such that the observer is fast and stable. The ω_m in (26) can be either the estimated speed $\omega_m{}^{\wedge}$, or the reference speed $\omega_m{}^*$.

From noise considerations, $\omega_m{}^*$ is employed.

B. Speed Estimation

The rotor speed ω_m depends on the rotor-flux speed

$$\omega_r{}^{\wedge} = \frac{d\hat{\theta}_r}{dt} = d[\tan^{-1}(\Psi_{rq}{}^{\wedge}/\Psi_{rd}{}^{\wedge})]/dt$$

or equivalent

$$\omega_r{}^{\wedge} = [\frac{d\Psi_{rq}{}^{\wedge}}{dt} . \Psi_{rd}{}^{\wedge} - \frac{d\Psi_{rd}{}^{\wedge}}{dt} . \Psi_{rq}{}^{\wedge}]/|\hat{\Psi_s}|^2, |\hat{\Psi_r}|^2 = \hat{\Psi}_{rd}{}^2 + \hat{\Psi}_{rq}{}^2 (27)$$

where, $\Psi_r{}^{\wedge} = \Psi_{rd}{}^{\wedge} + j . \Psi_{rq}{}^{\wedge}$ is given by (25).

The derivative estimation (27) gives fast estimation and compact computation. However, the estimation accuracy is based on the accuracy of ${}_r\Psi_r{}^{\wedge}$(25) estimation, which depends on ${}_s\Psi_s{}^{\wedge}$ and electromagnetic parameters. The derivative method is sensitive to noise via measured signals,

i.e., the current i_s.

The rotor speed estimation $\omega_m{}^{\wedge}$ is given by

$$\omega_m{}^{\wedge} = \omega_r{}^{\wedge} - \omega_{sl}{}^{\wedge}, \omega_{sl}{}^{\wedge} = \frac{R_s . T_0{}^{\wedge}}{P_n . |\hat{\Psi_r}|^2} (28)$$

Where, $\omega_{sl}{}^{\wedge}$ is the slip frequency, $\hat{T_o}$ is the estimated electromagnetic torque.

IV. SIMULATIONS AND DISCUSSIONS

To verify the SVM-DTC scheme based on input-output linearization and sliding-mode observer, simulations are performed in this section. The parameters of the induction motor used in simulation research are as follows

TABLE I. PARAMETERS OF INDUCTION MOTOR

Rated power P_N(kW)	3
Rated voltage U_N(V)	380
Rated voltage I_N(A)	6.8
Rated frequency (Hz)	50
Magnetic pole pairs p_n	2
Rated speed(rpm)	1420
Stators 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 ψ_s (Web)	0.8

fig. 5 shows the flux along the Q-axis and D-axis. The sampling period of the system is 100 μs, the reference stator flux used is 0.8 Wb and the command speed value is 5 rpm in both two systems. At startup, the system is unloaded, the load torque is changed to 17Nm at t=1s, then the load torque is changed from 17Nm to 10Nm at t=1.5s. Fig.6 and Fig.7 shows the flux linkages of Ψ_q and flux linkages of Ψ_d. In order to highlight validity of the sliding-mode observer, the stator resistance and rotor resistance are set to twice of the rated value in simulation. The simulation results are shown infig.8, fig.9and fig.10.

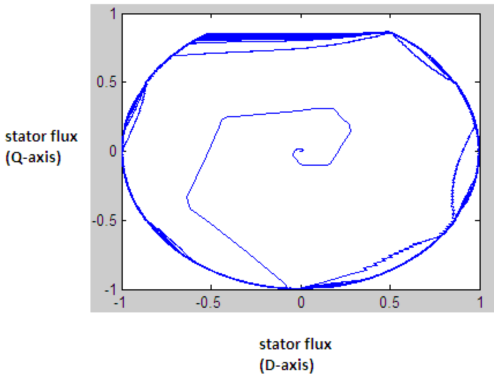

Fig.5 flux along Q-axix and D-axis

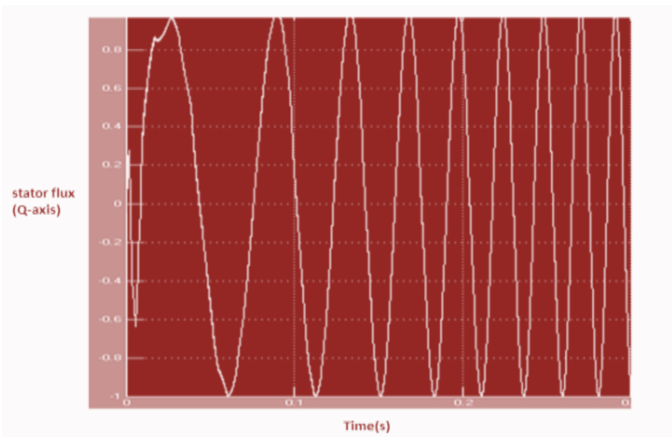

Fig.6 2-phase flux linkages of Ψ_q

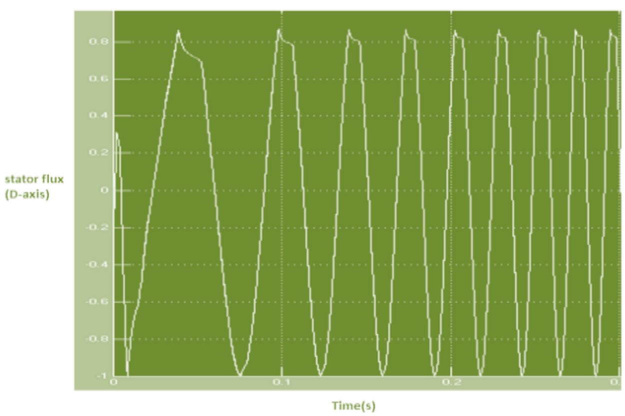

Fig.7 2-phase flux linkages of Ψ_d

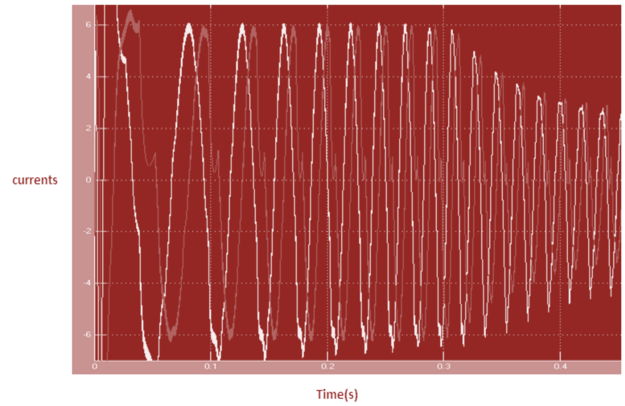

Fig.8 Current

Fig.9 Speed of induction motor

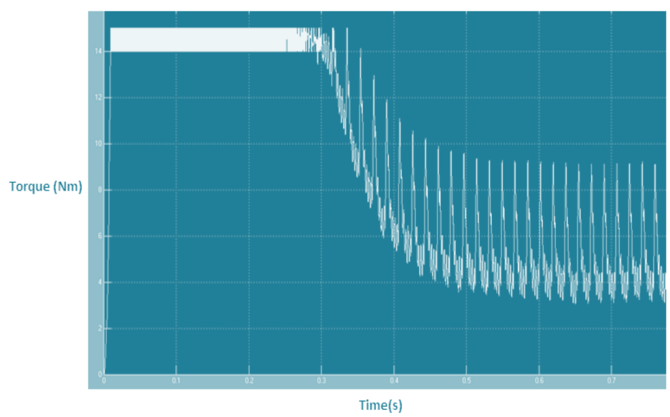

Fig.10 Torque developed

Fig 6 with fig 7, the SVM-DTC system based on feedback linearization has much smaller torque ripple than conventionalDTCsystem.Infig.7, the blue curve is the real speed of the SVM-DTC system, there done is the estimated speed of the system. The estimated speed is still well and truly at very low speed. From fig.9and fig.10,itcan be seen that the slide-mode observer can estimate the speed of motor well and truly ,even though there is well developed torque.

V. CONCLUSION

A new SVM-DTC scheme based on input-output line arization has been presented in this paper. By analyzing the torque wave forms, it shows that the SVM-DTC scheme based on input – output linearization can reduce torque ripples obviously .Simulations has been carried out. The simulation results verify that the SVM-DTC scheme based on input-output linearization achieves a reduction of torque ripple. The slide-mode observer can estimate stator flux well and truly even though there is exaggerated parameter variation. The speed estimation method is still validate very low-speed.

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