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A NEW APPROACH OF DTC SCHEME FOR INDUCTION MOTOR USING FLUX MODE OBSERVER

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Abstract –
With vector control techniques it is possible to control the torque and flux separately like DC motor. However, vector control implementations require coordinate transformations, separate voltage modulation block and voltage decoupling circuits. Direct Torque Control (DTC) provides very quick torque response without the complex field-orientation block and inner current control loop. DTC combined with Space Vector Modulation (SVM) ensures constant switching frequency and high-performance operation, both in the steady state and under transient conditions. Merits of the classic DTC transient behavior are preserved, while the steady-state operation is significantly improved. Closed loop torque and flux control is obtained by generating reference voltage vector which is realized by SVM. Advanced control strategies have been implemented to address various issues in DTC drives such as Sensor less Control with advanced speed observers and Stator Flux Observers.
The paper aims at studying the DTC, SVM-DTC and Sensor less Control with advanced flux observers. Two observers MRAS (Model Reference Adaptive System) Flux observer and sliding mode flux observers were studied in detail. Extensive simulations on MATLAB-SIMULINK platform are done for all these schemes.

I. Introduction

In addition to direct torque control (switching table based), instantaneous torque control yielding fast torque response can also be obtained by employing another direct torque control technique by using SVM technique.

It implements close loop digital control for both flux and torque in a similar manner as DTC, but the voltage is produced by a SVM unit. This way the DTC transient performance and robustness are preserved and the steady state torque ripple is reduced. Additionally, the switching frequency is constant and totally controllable.

A. Control Strategy of DTC-SVM

The proposed induction motor drive block diagram is shown in Fig.5-1. It operates with constant rotor flux, direct stator flux and torque control. The speed controller is a classical PID regulator which produces the reference torque. Only the dc-link voltage and two line currents are measured.

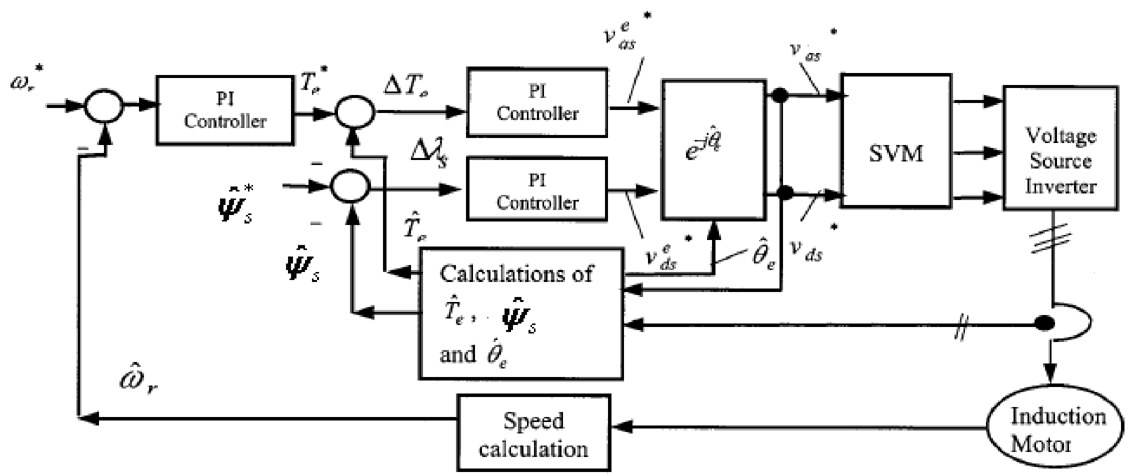


Fig.1 DTC-SVM based induction motor drive

Therefore the main theme of direct torque control is to regulate the torque and magnitude of flux directly without invoking any concept of field orientation. Following this essential concept, SVM based induction motor drives has two proportional integral (PI) type controllers to regulate the flux amplitude and 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 since the flux magnitude and torque can be regulated by the PI controllers.
The electromagnetic torque developed by induction motor is

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\psi_{ds}^s i_{qs}^s - \psi_{qs}^s i_{ds}^s) \quad Nm \tag{1}$$

Here we used induction motor model equations in stationary reference frame.

It implements close loop control for both flux and torque in a similar manner as DTC, but the voltage is produced by a SVM unit is explained in chapter 4. It receives the output of PI controllers that is reference voltage as shown in figure 5-2. Finally our aim is to generate this voltage by using SVM unit.

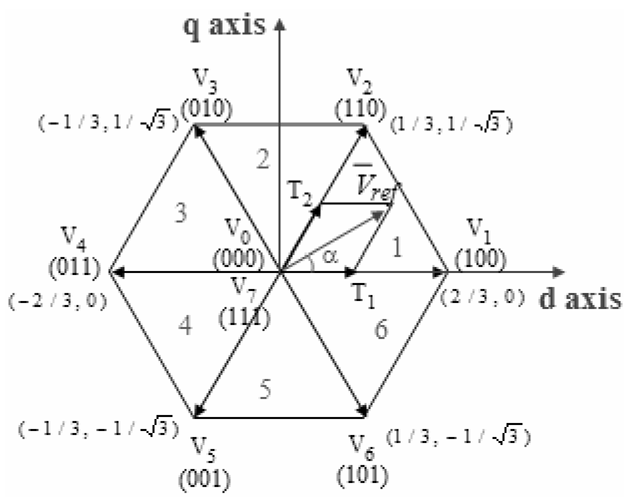


Fig.2 V_{ref} in space vector

The stator flux and torque close loop control is achieved by the DTC-SVM unit. In order to reduce the torque and flux pulsations and, implicitly, the current harmonics content, in contrast to the standard DTC, we do use decoupled PI flux and torque controllers and space vector modulation. Equations (5.4)-(5.5) are the inputs of SVM unit and it gives the control signal to inverter.

B.Torque and Flux Controller

The controller contains two PI regulators - one for flux and one for torque. It receives as inputs the stator flux and torque errors and generates the inverter's command signals. The dq components of the reference voltage vector in a stator flux reference frame are;

$$V_d^* = (K_{P\psi} + K_{I\psi}/s)(\psi_s^* - \psi_s) \tag{2}$$

$$V_q^* = (K_{PT} + K_{IT}/s)(T_e^{*_e} - T_e) + \psi_s \omega_{\psi s} \tag{3}$$

The inverter control signals are produced by the SVM unit. it receives the reference voltages (5.2) and (5.3) in a stator flux reference frame. The SVM principle is based on the switching between two adjacent active vectors and a zero vector during one switching period. The reference voltage vector defined by its length $|V_{ref}|$ (4) and angle α (5) in a stator reference can be produced by adding two adjacent active vectors &, if necessary, a zero vector V_0 OR V_7.

$$|V_{ref}| = \sqrt{V_d^{*2} + V_q^{*2}} \tag{4}$$

$$\alpha = \tan^{-1}\left(\frac{V_q^*}{V_d^*}\right) + \theta_{\psi s} \tag{5}$$

II. CONTROL OF INVERTERS AND SPACE VECTOR MODULATION TECHNIQUES

Sensors are very important in control of induction motor Drives. The position, speed and flux sensors improve the operating characteristics of induction motor drives. But at same time they increase the cost of the drives. Hence we are going for sensorless control. It is an important issue in implementing DTC of induction motor drives is to obtain accurate information about stator flux level and position for the entire speed range. Sensorless drives operate with out speed or position sensors, which increase their robustness and reduce the

equipment cost. Usually, full-order observers employ the linear, time-variable state-space model of the motor with the stator flux and the stator current as state variables. Various reference frames can be selected, but always only one reference frame was utilized for the observer realization. Whatever that frame is, at least one element of the matrix contains the rotor speed, and the observer has to be speed adaptive. Usually, the flux is estimated first, while speed estimation is the last step. Consequently, the estimated speed is affected by cumulative noise and delays. This estimate is fed back to the flux observer in the same, or subsequent sampling cycles. In this way, the accuracy of state estimation may progressively deteriorate. The speed adaptive observer has been proven stable, but undesirable effects, such as limit cycles, sensitivity to noise, or phase shifting tend to occur.
Use of two reference frames allows eliminating the speed adaptation. This feature is significant in drives that do not need the speed estimation for control. (Torque-controlled drives)

As it is the sensorless drives are still equipped with voltage and current sensors, signals from which are used in control algorithms. These sensors are inexpensive and installed away from the motor.

Sensorless drives employ a variety of estimators and observers of motor speed, torque and fluxes. An estimator calculates a given variables using the appropriate motor equations into which the measured values of stator voltage and current are substituted. Observers are more sophisticated with self adjustment feature. They are usually based on two or three independent estimators, whose output signals are compared. Their difference analogous to the control error in closed loop control system .it is used to adjust signals in the observer until the error is minimized. Here we are going to study the two types of flux observers.

1. Model Reference Adaptive System (MRAS).
2. Sliding Mode flux observer.

A. Model Reference Adaptive System (MRAS)

In this the estimator calculates the stator flux based on the induction motor equations (6)–(9). The inputs of the state estimator are the stator voltage and current space vectors. They are referred to a stationary reference frame.

$$u_s = R_s i_s + \frac{d\psi_s}{dt} + j\omega_e \psi_s \tag{6}$$

$$0 = R_r i_r + \frac{d\psi_r}{dt} + j(\omega_e - \omega_r)\psi_r \tag{7}$$

$$\psi_s = L_s i_s + L_m i_r \tag{8}$$

$$\psi_r = L_r i_r + L_m i_s \tag{9}$$

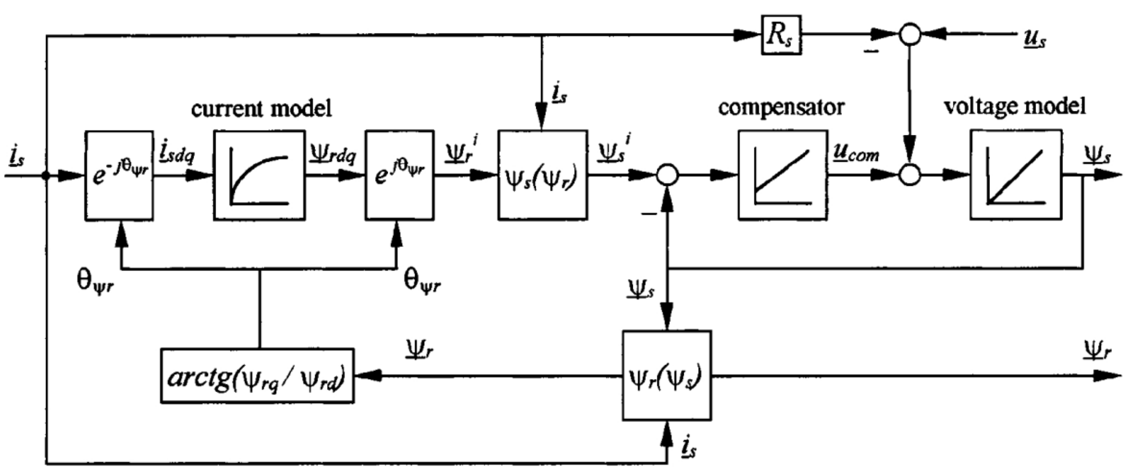


Fig.3 MRAS Flux Observer

The flux estimator is a full-order wide-speed-range stator and rotor flux observer. (see Fig.3). It contains two models the open-loop current model which is supposed to produce an accurate value, especially for low-speed operation, and the adaptive voltage model for wide speed range operation. The rotor flux current model estimator

(10) is deduced from (7) and (9) in a rotor flux reference frame (subscript “r”) using the measured stator current.

$$\psi_r = \frac{L_m}{(1+sT_r)} i_s - j\frac{\omega_e - \omega_r}{(1+sT_r)}\psi_r \qquad (10)$$

For rotor flux coordinates, the d,q rotor flux components are

$$\psi_{rd} = \frac{L_m}{(1+sT_r)} i_{sd} \qquad (11)$$

$$\psi_{rq} = 0 \qquad (12)$$

The output of the open loop current model is the stator flux calculated in stator coordinates is

$$\psi_s = \frac{L_m}{L_r}\psi_r + \frac{L_s L_r - L^2{}_m}{L_r} i_s \qquad (13)$$

The voltage model is based on (6.1) and uses the stator voltage and current measurements. For the stator reference frame, the stator flux is simply

$$\psi_s = \int (u_s - i_s R_s - u_{com})dt \, . \qquad (14)$$

In order to correct the value of estimated stator flux, to compensate for errors associate with pure integrator and stator resistance R_s measurement at low speed and to provide a wide speed range operation for the entire observer, the voltage model is adapted through a PI compensator.

$$u_{com} = (K_P + K_I \frac{1}{s})(\psi_s - \psi_s{}^{i}) \qquad (15)$$

Where K_P, K_I are PID gains.

The rotor flux ψ_r is calculated in a stator reference frame from the following equation

$$\psi_r = \frac{L_r}{L_m}\psi_s - \frac{L_s L_r - L^2{}_m}{L_r} i_s \qquad (16)$$

Hence finally we get the both stator and rotor fluxes.

B. SLIDING MODE OBSERVER

Accurate estimation of IM variables that are not directly measured is crucial for good operation of a sensorless drive. Usually, full-order observers employ the linear, time-variable state-space model of the motor. The motor model in arbitrary reference frame, which rotates with the speed ω_e, with the stator flux and the stator current as state variables, is

$$\frac{d}{dt}\begin{bmatrix}\varphi_s \\ i_s\end{bmatrix} = \begin{bmatrix}a_{11} & a_{12} \\ a_{21} & a_{22}\end{bmatrix}\begin{bmatrix}\varphi_s \\ i_s\end{bmatrix} + \begin{bmatrix}b_1 \\ b_2\end{bmatrix} u_s \qquad (17)$$

$$= Ax + Bu_s$$

$$i_s = Cx \qquad (18)$$

Where

$$a_{11} = -j\omega_e \; (6.7)$$

$$a_{12} = -R_s$$

$$a_{21} = \left[\frac{r_r}{L_r} - j\omega_e\right]\frac{L_r}{\sigma} \; (6.8)$$

$$a_{22} = j(\omega_r - \omega_e) - \frac{L_r r_s}{\sigma} - \frac{L_s r_r}{\sigma}$$

$$b_1 = 1 \;, \; b_2 = \frac{L_r}{\sigma}; \; (6.9)$$

$$C = [0 \quad 1]$$

$$\sigma = L_s L_r - M^2 .$$

$$\frac{d}{dt}[x] = Ax + Bu_s + K\,\text{sgn}(i_s - \hat{i}_s) \qquad (19)$$

Where the gain K is selected so as the observer is stable. Other dynamic models of the motor can be used instead of (17) and (18). Various reference frames can be selected, but always only one reference frame was utilized for the SMO realization. Whatever that frame is, at least one element of the matrix contains the rotor speed, and the observer has to be speed adaptive. Usually, the flux is estimated first, while speed estimation is the last step. Consequently, the estimated speed is affected by cumulative noise and delays. This estimate is fed back to the flux observer in the same, or subsequent sampling cycles. In this way, the accuracy of state estimation may progressively deteriorate. The speed adaptive observer has been proven stable, but undesirable effects, such as limit cycles, sensitivity to noise, or phase shifting tend to occur.

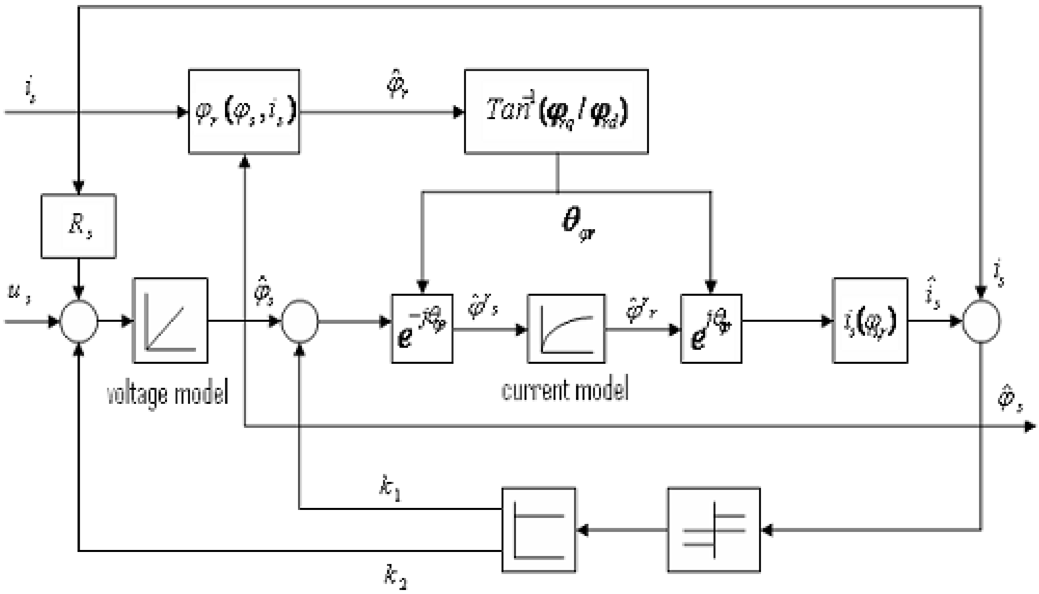


Fig.4 Sliding Mode Flux Observer.

An inherently sensorless SMO, shown in Fig.4, has been developed. It is input–output equivalent to (17), and using two reference frames allows eliminating the speed adaptation. This feature is significant in drives that do not need the speed estimation for control (torque-controlled drives) and it is expected to produce better results than (17).
The induction motor stator current is

$$i_s = \frac{L_r \varphi_s + L_m \varphi_r}{\sigma} \tag{20}$$

Replacing (6.15) in the second equation of (6.14), the SMO is

$$\frac{d}{dt}\hat{\varphi}_s = -r_s i_s - j\omega_e \varphi_s + u_s + K_1 \operatorname{sgn}(i_s - \hat{i}_s) \tag{21}$$

$$\frac{d}{dt}\hat{\varphi}_r = \frac{L_r M}{\sigma}\hat{\varphi}_s - \left[\frac{L_s r_r}{\sigma} + j(\omega_e - \omega_r)\right]\hat{\varphi}_r + K_2 \operatorname{sgn}(i_s - \hat{i}_s) \tag{22}$$

$$\hat{i}_s = \frac{L_r \hat{\varphi}_s - L_m \hat{\varphi}_r}{\sigma} \tag{23}$$

Since only algebraic manipulations were involved, the sliding observers (18) and (20)–(23) are equivalent.

In order to eliminate the rotor speed adaptation, the stator equation (21) is implemented in stator reference frame, and the rotor equation (22) is implemented in rotor flux frame (superscript "r"), which rotates with rotor flux speed $\omega_{\varphi r}$,

$$\frac{d}{dt}\hat{\varphi}_s = -r_s i_s + u_s + K_1 \operatorname{sgn}(i_s - \hat{i}_s)$$

$$\frac{d}{dt}\hat{\varphi}_{rd} = \frac{L_r M}{\sigma}\hat{\varphi}_{sd} - \frac{L_s r_r}{\sigma}\hat{\varphi}_{rd} + \operatorname{Re}(K_2 \operatorname{sgn}(i_s - \hat{i}_s))$$

The estimated position of the rotor flux frame is obtained as, where another estimate of the rotor flux, in the stator frame, has been calculated as

$$\theta_{\psi r} = \tan^{-1}\left(\frac{\hat{\psi}_{rq}}{\hat{\psi}_{rd}}\right)$$

In this manner we observe the accurate values of stator and rotor fluxes.

III. SIMULATION DIAGRAMS

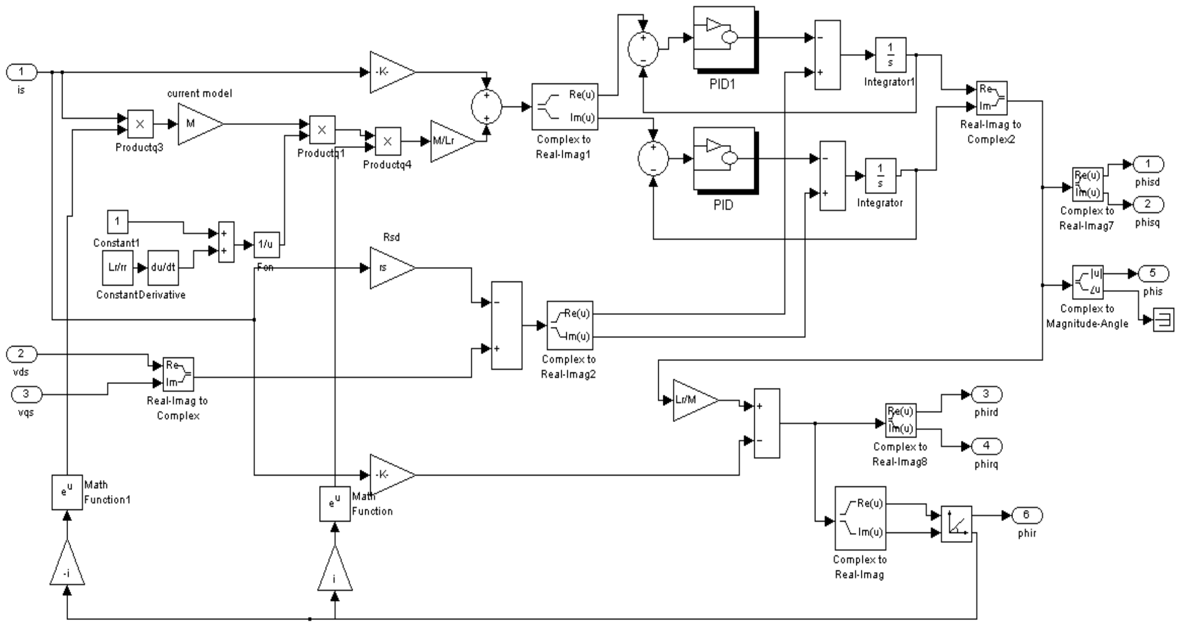


Fig.5 MRAS flux observer simulation diagram

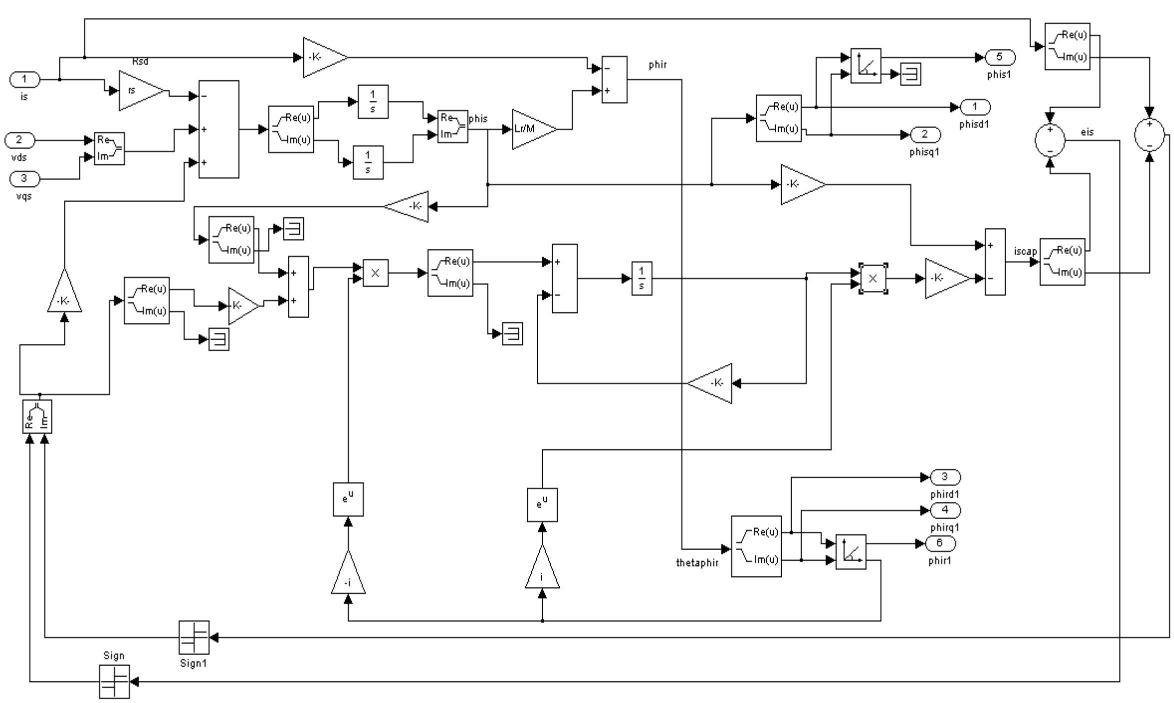


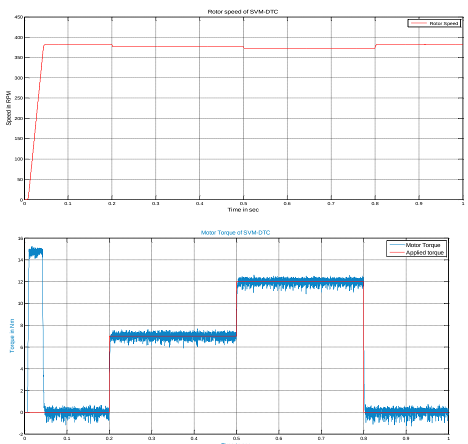
Fig.6 sliding mode flux observer simulation diagram

IV. INDUCTION MACHINE PARAMETERS

R_s=7.83 ohms % Stator resistance
R_r=7.55 ohms % Rotor resistance
L_s=0.4751 H % Stator inductance
L_r=0.4751 H % Rotor inductance
M=0.4535 H % Mutual inductance
P=4; % Poles
J=0.013 % Inertia
V_{dc}=2*155 %D C Link voltage
P=1.1kw %power
t_{ss}=100e-6; % Sampling time

V.SIMULATION RESULTS

i.Simulation Results of SVM-DTC



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Torque and Speed results of SVM-DTC

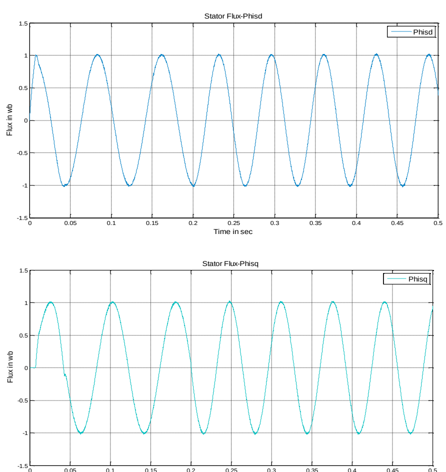


Fig. 8 d-axis and q-axis stator fluxes of SVM-DTC

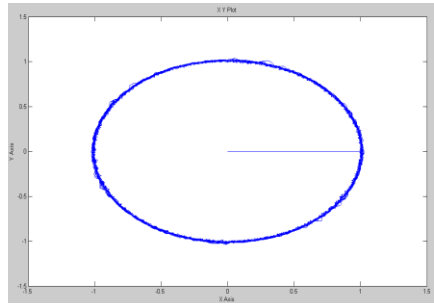


Fig. 9 Stator flux vector of SVM-DTC

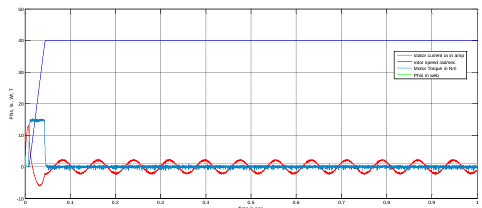


Fig. 10 Rotor Speed, Motor Torque, Stator Current and Stator Flux magnitude results of SVM-DTC.

ii. Simulation Results of MRAS flux observer based SVM-DTC

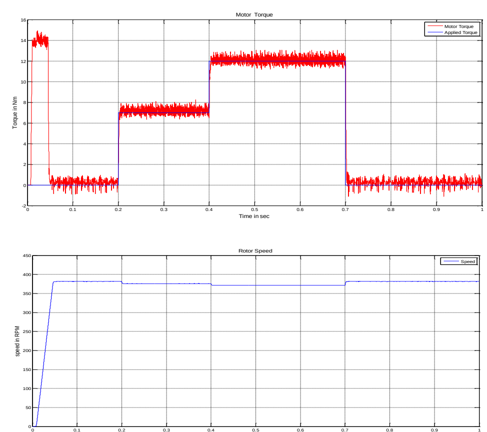
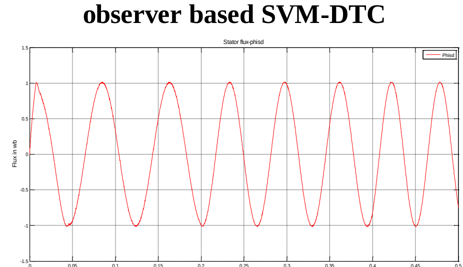


Fig.11 Torque and Speed results of MRAS observer based SVM-DTC



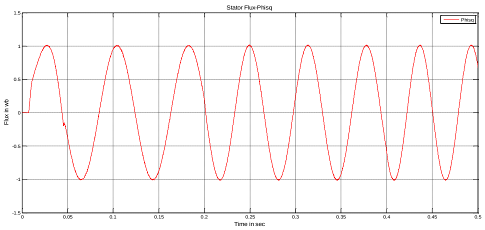


Fig.12 d-axis and q-axis fluxes of MRAS observer based SVM-DTC

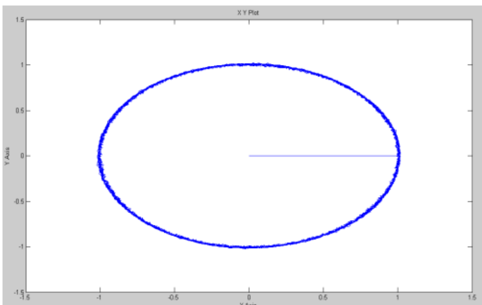


Fig.13 Stator flux vector of MRAS observer based SVM-DTC

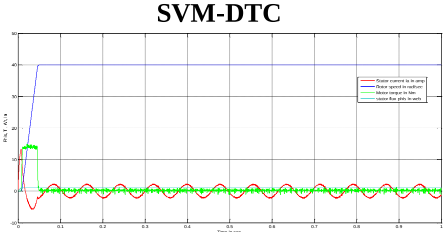


Fig.14 Rotor Speed, Motor Torque, Stator Current and Stator Flux magnitude results of MRAS observer based SVM-DTC

V. CONCLUSIONS

In this dissertation report, the Space Vector Modulation for DTC is studied thoroughly and implemented on MATLAB_SIMULINK platform. Initially, the model of an induction machine is analyzed with its complete theoretical details and the required equations. This is the required foundation to understand the DTC schemes in detail. The results of classical DTC were compared with the SVM based DTC. It is observed that there is considerable torque reduction because of constant switching frequency. This scheme, while preserving the merits of classical DTC in transient period, brings in the satisfactory steady state operation. Further, DTC-SVM with two types of observers was simulated: Model Reference Adaptive System (MRAS) and Sliding mode flux observer. Both used two reference frames to avoid speed adaptation.

Finally conclusions are:

- DTC-SVM strategy realizes almost ripple-free operation for the entire speed range. Consequently, the flux, torque, and speed estimation is improved.
- The fast response and robustness merits of the classical DTC are entirely preserved.
- The switching frequency is constant and controllable. In fact, the better results are due to the increasing of the switching frequency. While for DTC a single voltage vector is applied during one sampling time, for DTC-SVM a sequence of six vectors is applied during the same time. This is the merit of SVM strategy.
- An improved MRAS estimator based on a full-order rotor flux estimator as reference model was proposed and tested at high and low speeds.
- Finally sliding mode flux observer based SVM-DTC was presented and it is observed that it is better suitable for nonlinear system, it has disturbance rejection property and is robust in nature.

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