Torque Ripple minimization techniques in direct torque control induction motor drive

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Abstract—**This paper considers direct torque control strategies in induction motor drive to minimize torque ripples. Spacevector modulation and modified space vector control concept is implemented to design the controller. Basic DTC method suffers from torque ripples problem and switching frequency variation.[1] Torque ripples are minimized using space vector modulation technique but execution time in three phases to two phase transformation and reference voltage calculations requires more, comparing with other method by determination of effective time vectors. Sector and angle determination and procedure of determination of reference vector is eliminated in modified Space vector modulation method. Simulation studies have been carried out for three methods.Basic DTC results in, change in flux, change in speed and change in load are simulated in Matlab and compared with other two strategies on the same platform.This paper mainlyhighlights performance of the drive in dynamic torque and flux response.**

Keywords—Basic DTC;SVPWM;torque ripple

I. INTRODUCTION

Worldwide on industrial, commercial platforms, induction motors are used. Comparing with all speed control methods stator voltage variation method is adopted universally in which change in the magnitude of stator voltage, changes the speed. Due to constant air gap flux requirement, along with magnitude of stator voltage supply frequency also changes to keep v/f ratio constant. Variable frequency is required to vary rotor speed as speed depends on synchronous speed of rotating magnetic field. Variable magnitude of stator voltage is required to limit stator current as at low frequency impedance reduces and stator current increases.

If speed control of slip ring induction motor is considered then external resistances are added through slip rings. Addition of these resistances introduces more copper loss and comparing with all methods it leads to one of the disadvantages of slip ring induction motor.

Speed of induction motor can be controlled by following control methods:

Scalar Control: voltage / frequency (v/f) is the basic, economical and simple control used in most of the industries. It is called as scalar as magnitude of stator voltage and frequency is varied to vary the speed. It isopen loop and less precise controls as far as speed and torque variation is concerened.Flux and torque are controlled indirectly. In scalar control parameters are identified continuously so the speed variation is 2 to 2.5 % and dynamic response is around 45 to 50 ms.

Vector Control- It is closed loop control and in this control current and voltages are continuously sensed. It is advanced control method and worldwide accepted. It is precise and accurate speed and torque control. due to complexity in computational algorithms its area is limited.

Direct torque control- DTC is an alternative advanced speed control method to vector control .Due to simplicity in algorithm and control it is popular. Its performance is also comparable with vector control. Speed control of induction motor is possible in four quadrants with help of DTC. By simple control algorithm it possible to control flux and torque directly with appropriate stator voltage vector.

II .BASIC DTC SCHEME

Fig.1 shows schematics of Basic DTC,in which torque and flux are controlled directly by selection of inverter voltage space vector from a look up table.[4]

The electromagnetic torque can be expressed in vector form as given in Eqn. (1)-(3) as:

$$\overline{T_e} = \frac{3}{2}\left(\frac{p}{2}\right)\overline{\lambda_s} \times \overline{i_s} \quad (1)$$

and

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)\frac{L_m}{L_r L_s^{'}}\psi_r \times \psi_s \quad (2)$$

Therefore, magnitude of torque becomes

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)\frac{L_m}{L_r L_s^{'}}|\psi_r||\psi_s|\sin\gamma \quad (3)$$

$$\Delta T_e = \frac{3}{2}\left(\frac{p}{2}\right)\frac{L_m}{L_r L_s^{'}}|\psi_r||\psi_s + \Delta\psi_s|\sin\Delta\gamma \quad (4)$$

Where γ is the angular displacement of stator flux with respect to rotor flux.

Due to high time constant, the rotor flux does not change instantly and stator flux changesdue to change in stator voltage V_s, the corresponding change of γ angle is $\Delta\gamma$,so the change in torque ΔT_e expression is given by Eqn. (5) as :

$$\Delta T_e = \frac{3}{2}(\frac{p}{2})\frac{L_m}{L_r L_s'}|\psi_r||\psi_s + \Delta\psi_s|\sin\Delta\gamma \qquad (5)$$

In the controller torque error, flux error and stator flux position is estimated during each sampling period and compared with reference value and from look up table selects expected value of stator voltage among eight values and accordingly switching of inverter takes place. Schematic of Basic DTC is shown in Fig.1.

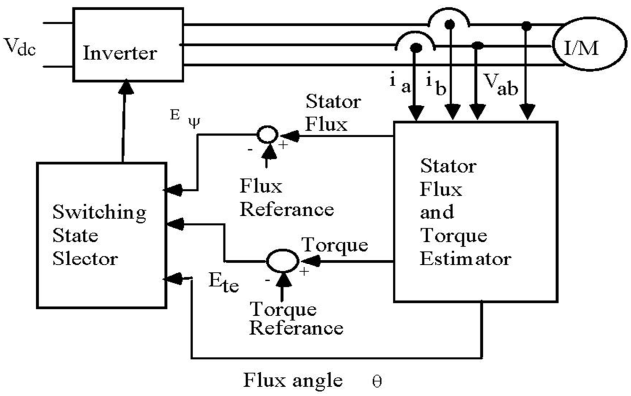

Fig.1: Basic DTC scheme

FEATURES of BASICDTC

- Inverter output voltage vector is only controlling parameter.
- Variations s in stator flux are controlled by change in the stator voltage.
- Any change in the stator flux space vector leads to change in the torque value.

DISADVANTAGE ofBASICDTC

Hysteresis band control generates flux and torque ripples and switching from one state to another is not smooth-leads to switching loss.

II .SPACE VECTOR DTC SCHEME WITH SECTOR AND ANGLE DETERMINATION

Fig.2 shows schematics of SVM-DTC of induction motor. Two PI controllers are implemented, one to control the flux and other for the torque. Stator flux error and torque error are single inputs to each of the controller. DQ components of reference voltage vectors are the two corresponding outputs of the PI controllers. The roll of SVM controller is to produce three time signals and next three voltage vectors as an output of the inverter.

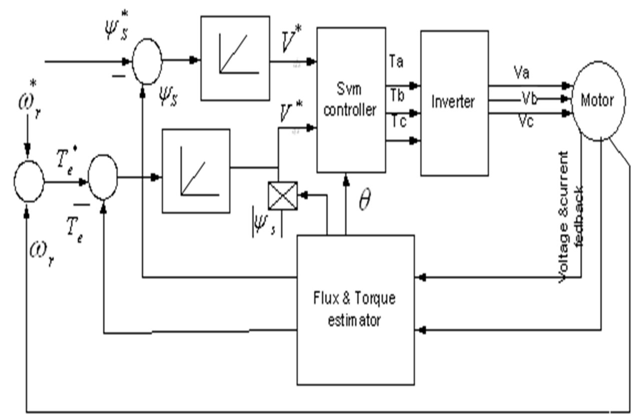

Fig. 2: SVM DTC scheme with sector and angle determination

$$V_{sd} = (k_p + \frac{k_I}{s})(\psi_s^* - \psi_s) \qquad (6)$$

$$V_{sq} = (k_p + \frac{k_I}{s})(T_e^* - T_e) + \psi_s\omega_s \qquad (7)$$

Andelectromagnetic torque is given by Eqn. (8)

$$T_e = 1.5 * \frac{p}{2}\psi_s i_{sq} \qquad (8)$$

PI controller is present in the torque channel. [5] It controls the torque value even if the estimation has error in the last term. The error in the magnitude of flux value is input of one PI controller produces d axis component of voltage vector.For each sampling period Ts, approximate the voltage will be given as:

$$V_{sd} = R_s i_{sd} + \Delta\psi_s / T_s \qquad (9)$$

At high speed, the ignoring $R_s i_{sd}$ voltage drop, voltage becomes proportional to change in flux $\Delta\psi$ and the switching frequency1/Ts. At low speed the $R_s i_{sd}$ drop is considerable. Calculation of voltage term requires instantaneous speed and the magnitude of stator flux. The SVM unit generates the inverter control signals.[6] It receives reference voltages in a stator reference frame. The switching between two adjacent active voltage vectors and zero vectors during one switching period is the basic principle of SVM technique.

$$V = \sqrt{V_d^{*2} + V_q^{*2}}$$
$$\alpha = \arctan\frac{V_q^*}{V_d^*} + \theta_s \qquad (10)$$

Where θ_s is stator flux position.

ADVANTAGES OF SVPWM-DTC

- SVM-DTC technique gives ripple free operation for entire speed range. Improvement in flux, torque, speed response.
- Response is fast and controller is robust like BASIC DTC
- Switching frequency is high and controllable.

III MODIFIED SPACE VECTOR DTC SCHEME

(Without angle and sector determination)

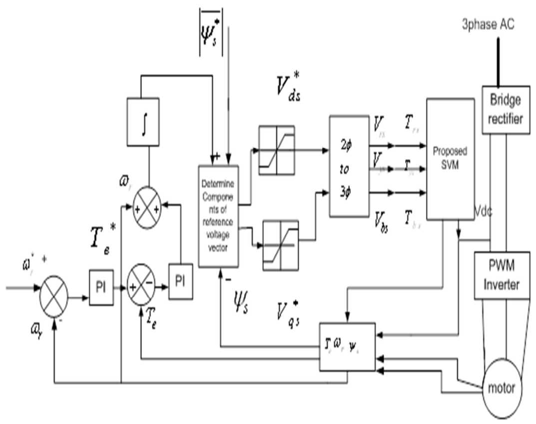

Fig.3: Modified SVM DTC scheme without angle and sector determination

Fig no.3 is the block diagram of Modified SVMDTC scheme without angle and sector determination in which The dq components of the reference vector are constructed by respective flux error components without PI regulators.[7]

The procedure is as follows:

$$V_s = R_s i_s + \frac{d}{dt}\psi_s \quad (11)$$

If resistance of stator winding is negligible, Eqn. (11) can be modified as:

$$d\psi_s = \overline{V_s}\, dt \quad (12)$$

If the time interval is small, this equation can be written as:

$$\Delta\psi_s = \overline{V_s}\,\Delta t \quad (13)$$

Eqn. (13) can be re-written as

$$\Delta\psi_{sd} + j\Delta\psi_{sq} = (V_{sd} + jV_{sq})\Delta t \quad (14)$$

Comparing real and imaginary parts of Eqn. (14) gives:

$$V_{sd} = \frac{\Delta\psi_{sd}}{\Delta t} = \frac{\psi^*_{sd} - \psi_{sd}}{\Delta t} \quad (15)$$

$$V_{sq} = \frac{\Delta\psi_{sq}}{\Delta t} = \frac{\psi^*_{sq} - \psi_{sq}}{\Delta t} \quad (16)$$

Where Δt is equal to the sampling time Ts. Hence dq components of reference voltage vector $V_s = (V_{sd} + jV_{sq})$ are determined in a simple manner as given by Eqns. (15) and (16) without any reference frame transformation. Speed of the reference flux space vector $\overline{\psi}^*_s$ is derived by addition of slip speed and actual rotor speed. The actual synchronous speed of stator flux vector $\overline{\psi}_s$ is calculated from machine model. After each sampling interval, actual stator flux vector $\overline{\psi_s}$ is corrected by the error and it tries to attain the reference flux vector $\overline{\psi}^*_s$. Thus flux error is minimized in each sampling interval. The dq components of reference voltage vectors are transformed to three phase reference voltages V_{rs}, V_{ys}, V_{bs} which gives voltage signals for SVM.[8] These voltages can be converted to corresponding three imaginary times T_{rs}, T_{ys}, T_{bs} These three imaginary times can generate reference voltage signals. These are following steps to find three reference voltage vectors:-

Step 1: Calculate three phase voltages from dq axis component of reference voltage vector.Eqn.(17)

$$\begin{aligned} V^*_{rs} &= V_{sd} \\ V^*_{ys} &= -\frac{1}{2}V_{sd} + \frac{\sqrt{3}}{2}V_{sq} \\ V^*_{bs} &= -\frac{1}{2}V_{sd} - \frac{\sqrt{3}}{2}V_{sq} \end{aligned} \quad (17)$$

Step 2: calculate three imaginary times with respect to three reference voltages Eqn.(18)

$$\begin{aligned} T_{rs} &= \frac{V^*_{rs}}{V_{dc}} \times \frac{T_s}{2} \\ T_{ys} &= \frac{V^*_{ys}}{V_{dc}} \times \frac{T_s}{2} \\ T_{bs} &= \frac{V^*_{bs}}{V_{dc}} \times \frac{T_s}{2} \end{aligned} \quad (18)$$

From three times on r,y,b axes three corresponding voltages are generated voltages and compare with the symmetrical triangular wave to generate trigger pulses for SVM-INVERTER and corresponding voltage is applied to Induction Motor to produce necessary torque.

ADVANTAGES OF SVM-DTC SCHEME

(without sector and angle determination):

- Modified SVM-DTC technique gives ripple free operation for entire speed range. Improvement in flux, torque, speed response.
- Response is fast and controller is robust like BASIC DTC.
- Calculation of angle and sector determination is eliminated; it does not require any reference frame transformation.
- Less memory space and computation time requires.

IV SIMULATION RESULTS

The Induction motor model is simulated in Mat lab. Simulation studies have been carried out for SVM-DTC and Basic DTC using Matlab/Simulink software. Ode1 Euler's method with sampling time of 100µs is used. Reference flux is 1.0 wb and speed is changed from 750 rpm to 1350 rpm. Load torque is zero in the flux variation and speed variation methods and load is changed from 0 to 10 Nm at 0.5 sec in load variation method.

Performance point of view,Basic DTC, SVM-DTC (with sector and angle) and SVM-DTC (without sector and angle) are studied in simulation. Stator flux has been plotted as shown in Fig. 4(a)-(c) respectively for three schemes. Whereas change in load torque has been shown in Fig.5(a)-(c) respectively.

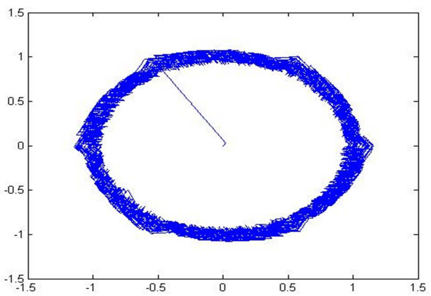

Fig. 4 (a):DQ Axis Stator Flux plot- Basic DTC

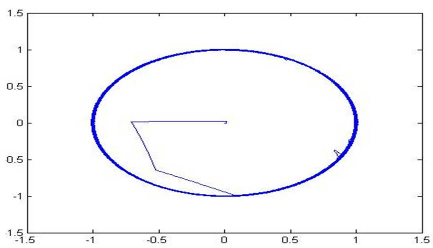

Fig. 4 (b):DQ Axis Stator Flux plot- Modified SVM DTC (withsectorand Angle)

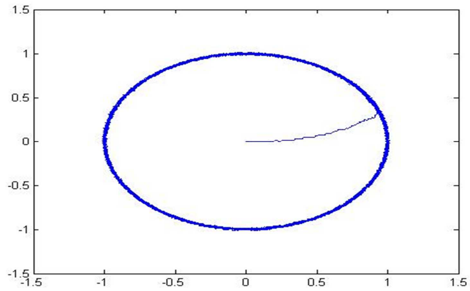

Fig. 4 (c):DQ Axis Stator Flux plot- Modified SVM DTC (without sector and Angle)

Comparing with Basic DTC and SVM-DTC(with sector and angle) flux plot, above flux plot is sharp, without starting transients means flux ripples are less with smooth starting.

2. Change in the load Torque:

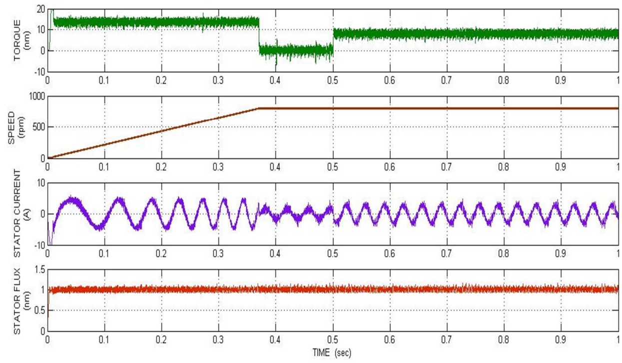

Fig. 5 (a): Basic DTCChange in the load from 0 to 10nm at 0.5 sec

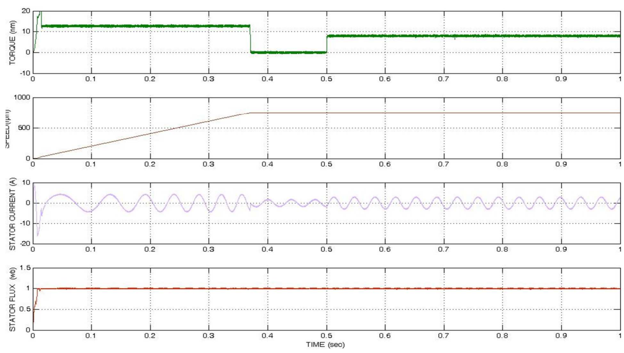

Fig. 5 (b):SVM-DTC(with sector and angle) Change in the load from 0 to 10 nm at 0.5 sec

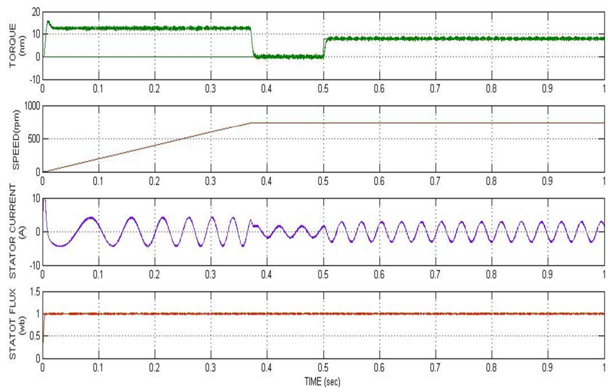

Fig. 5 (c):SVM-DTC(without sector and angle) Change in the load from 0 to 10 nm at 0.5 sec

Observations (Basic DTC):

- When load is changed from no load to rated value, torque changes to rated value with staring transients with more ripples and 50 % variation from the rated value is observed.
- Speed attains its rated value smoothly.
- Ripples are observed in stator flux. Nearly 20 % variation is observed from reference value.
- Ripples are observed in stator phase currents as ripples in the stator flux.

Observations(SVM- DTC with sector and angle):

- When load is changed from no load to rated value, torque changes to rated value with staring transients and ripples are less and 10 % variation from base torque value is observed.
- Speed attains its base value smoothly.
- Ripples are less observed in stator flux only 4%variations from the reference flux value.
- Ripples are less in stator phase currents.

SVM-DTC (with sector and angle) enhances performance of Induction Motor drive with better complexity.

Observations:(SVM-DTC without sector and angle)

- When load is changed from no load to rated value, torque changes to rated value without staring transients with less ripples.10 % variation from base torque value.
- Speed attains its base value smoothly.
- Ripples are observed in stator flux. 4% variation from reference value is observed.
- Ripples are less in stator phase currents.

SVM-DTC(without sector and angle) enhances performance of Induction Motor drive with less computational time.

3. Change in the speed:

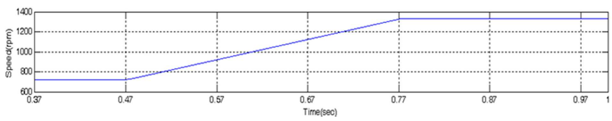

Fig. 6: Change in the speed from750 RPM TO 1350 rpm)

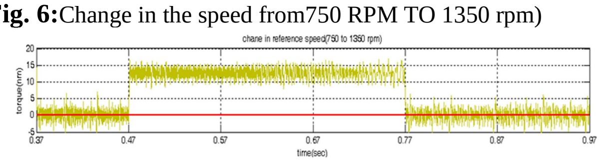

Fig. 7 (a): BasicDTC

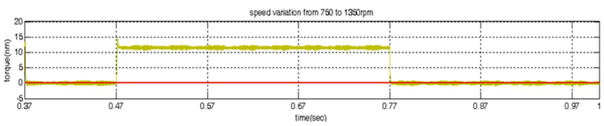

Fig. 7 (b):SVM DTC (with sector and angle)

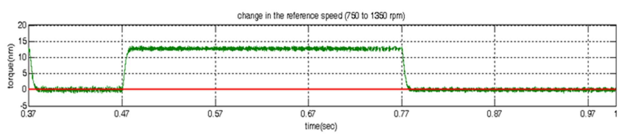

Fig. 7 (c):SVM DTC (without sector and angle)

Observations:

- When speed change takes place from 750 to 1350 rpm,In the basic DTC more torque ripples are observed. Torque variation is 50%
- In SVM DTC and Modified SVM DTC(without sector and angle) torque ripples are almost reduced 7 to 8 %

4. Change in the stator flux from 1 to 0.7 wb

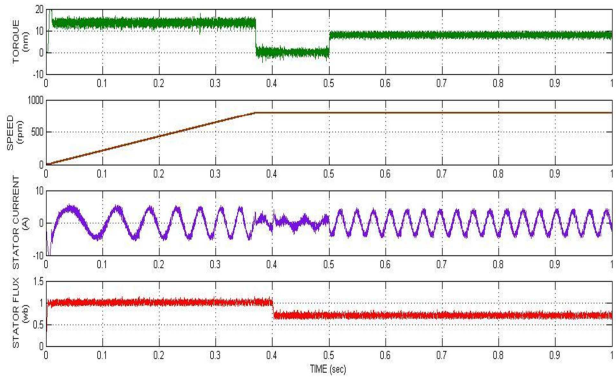

Fig. 8: Basic DTC(change in flux)

Observations:

- When flux is reduced to 0 .7mwb at 0.4 sec, basic DTC scheme responds the change and torque settles after 0.1 sec after the change.
- No change in the speed is observed.
- Change in magnitude of stator currents and ripples are observed during 0.4 sec to 0.5 sec.
- Similar response is observed for SVM DTC (With sector and angle) and SVM-DTC (without sector and angle) with less ripples in torque and stator current.

V. CONCLUSION

- Torque ripples are less in SVM-DTC method PI controllers used in SVM-Controller improves performance in torque response as proportional controller eliminates steady state error and integral controller eliminates overshoot of the response. Saturators are used to keep voltage value within limit. While hysteresis comparators used in conventional method produces torque ripples as they accept any value of torque within the bandwidth chosen.As bandwidth is more ripples are more and as bandwidth is less due to high frequency switching.
- Smooth torque development in SVM-DTC method, at no load condition when speed is varied from half to rated speed, torque is developed smoothly in SVM-DTC both methods.

In SVM-DTC (without sector and angle method) PI controllers are not used hence rise time is more than conventional and SVM-DTC(with sector and angle method)

- Simulation results of both SVM-DTC methods are same but for without sector and angle method less computation time is required than SVM-DTC with sector and angle as calculations of reference voltage, sector and angle are eliminated.

As shown, the Fig.9 represents the experimental setup in the machines laboratory on which experimental validation is going on.

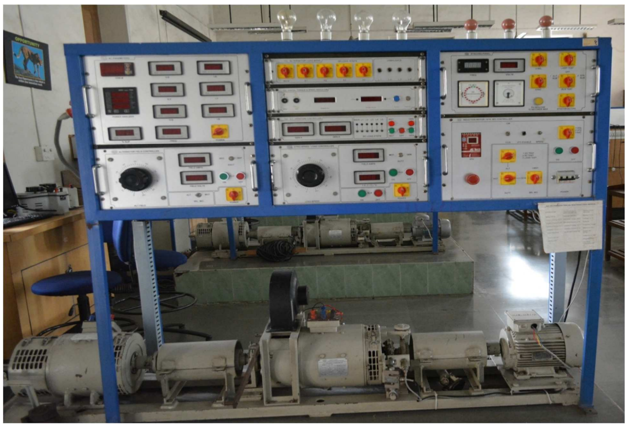

Fig.9: Experimental set up

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