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Space Vector Modulation based Direct Flux and Torque Control Induction Motor drive

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Abstract

Direct flux and torque control (DFTC) is the control mechanism used in ac drives. The standard DFTC drive has hysteresis controllers. DFTC drives with hysteresis controllers are mostly affected by high flux ripple, high ripple content in torque and changeable switching frequency. It is possible to eliminate these problems with the help of space vector modulation (SVM) technique. In the proposed space vector modulation based direct flux and torque control (SVM-DFTC) method space vector modulator is used instead of lookup table or switching table and proportional-integral (PI) controllers are used instead of hysteresis controllers. The drive system performance is analyzed by MATLAB/SIMULINK software.

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I. INTRODUCTION

Most of the electrical loads are operated at wide range of speeds. These loads are mostly driven by electric motors. The majority of the electric drives employ DC or AC motors. The major drawbacks of DC motor are the bulky construction, less reliable, low efficiency and the inclusion of commutator and brushes, which require frequent maintenance [1]. To overcome this drawback and also due to the availability of reliable power converter technology AC motors are tremendously used. In most of the high performance and high efficiency AC drives induction motors (IMs) are preferred. Owing to the benefits like simple in construction, easy to maintain, low cost, robustness make these more popular. In recent years, several techniques are created for efficient use of IM.

AC drives can be controlled by the most excellently known technique created by Takahashi [2] and is termed as direct flux and torque control (DFTC). The term itself indicates that, this control technique operates mainly on the flux and torque errors. To obtain the flux and torque errors, the actual values of flux and torque are correspondingly compared with the reference values of flux and torque and the flux and torque errors can be regulated by controlling the inverter states. Both the magnitude and angle of flux are required in case of standard DFTC. In this standard DFTC, the stator measured quantities such as voltage and current are obtained from stator voltage model, in order to achieve the flux extensively. As compared to field oriented control (FOC) technique, standard DFTC technique include the use of hysteresis band comparators rather than torque and flux controllers/regulators

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[3],[4].In order to replace FOC's coordinate transformations and pulse width modulation (PWM) signal generators, standard DFTC employs switching tables to choose the inverter state-based switching procedure [5],[6]. Although, it has the advantages like simple scheme, quick torque response and less sensitivity toward parameter uncertainties there are several drawbacks like high flux ripple, high torque ripple and variable switching frequency [7]. Owing to these disadvantages the performance of the IM is degraded.

To eliminate the disadvantages of standard DFTC, Space Vector Modulation based DFTC (SVM-DFTC) approach is implemented for IM drive. The drawbacks of standard DFTC are due to the hysteresis comparators [8] and switching table used in a system. Therefore, in case of SVM-DFTC, space vector modulator is used instead of lookup table/switching table and proportional-integral (PI) regulators are used instead of hysteresis regulators. Specifically in order to get an inverter constant switching frequency, space vector modulation (SVM) is implemented by DFTC with an IM drive.

The standard DFTC approach relies mostly on instantaneous values and the control signals specifically computed from the inverter. The control logic in the SVM-DFTC approach is according to average values while the inverter switching signals are obtained from the space vector modulation. This is the key distinction between standard DFTC and SVM-DFTC. The Simulink waveforms are provided to demonstrate the performance of the proposed SVM-DFTC technique and the simulation is performed by MATLAB/SIMULINK software.

II. MATHEMATICAL MODELING OF INDUCTION MOTOR

In case of DFTC the IM is modeled in stationary reference frame can be represented in equation format is as follows [9]:

Voltage equations:

$$V_{ds} = \frac{d}{dt}\psi_{ds} + R_s i_{ds} \qquad (1)$$

$$V_{qs} = \frac{d}{dt}\psi_{qs} + R_s i_{qs} \qquad (2)$$

$$0 = \frac{d}{dt}\psi_{dr} + R_r i_{dr} + \omega_r \psi_{qr} \qquad (3)$$

$$0 = \frac{d}{dt}\psi_{dr} + R_r i_{qr} - \omega_r \psi_{dr} \qquad (4)$$

Flux linkage equations:

$$\psi_{ds} = \int (V_{ds} - R_s i_{ds})dt \qquad (5)$$

$$\psi_{qs} = \int \left(V_{qs} - R_s i_{qs}\right)dt \qquad (6)$$

$$\psi_{dr} = \int \left(-\psi_{qr}\,\omega_r - R_r i_{dr}\right)dt \quad (7)$$

$$\psi_{dr} = \int \left(-\psi_{qr}\,\omega_r - R_r i_{dr}\right)dt \quad (8)$$

Electromagnetic torque

$$T_e = \frac{3}{2}\frac{p}{2}\left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}\right) \quad (9)$$

Rotor speed

$$\omega_r = \int \frac{p}{2J}(T_e - T_L)dt \qquad (10)$$

Where

V_{ds} and V_{qs} = d-axis and q-axis Stator Voltages
ψ_{ds} and ψ_{qs} = d-axis and q-axis Stator Fluxes
ψ_{dr} and ψ_{qr} = d-axis and q-axis Rotor Fluxes
R_s and R_r = Stator Resistance and Rotor Resistance
i_{ds} and i_{qs} =d-axis and q-axis Stator Currents
i_{dr} and i_{qr} = d-axis and q-axis Rotor Currents
ω_r =Angular Speed of the Rotor in rad/s
p= Poles count
J = Moment of Inertia
T_e =Electromagnetic Torque in N-m
T_L = Load Torque in N-m

III. DIRECT FLUX AND TORQUE CONTROL

The standard DFTC is a closed loop control approach uses two loops for controlling, one is for controlling the flux and another one is for controlling the torque. For this purpose two hysteresis regulators are used. The flux hysteresis regulator is useful for monitoring the actual value of flux with reference value of flux and the torque hysteresis regulator is useful for monitoring the actual value of torque with reference value of torque. Diagrammatic representation of standard DFTC with IM drive is as shown in the fig.1. Based on the results obtained from the hysteresis regulators, the inverter switching states can be selected by using the lookup table.

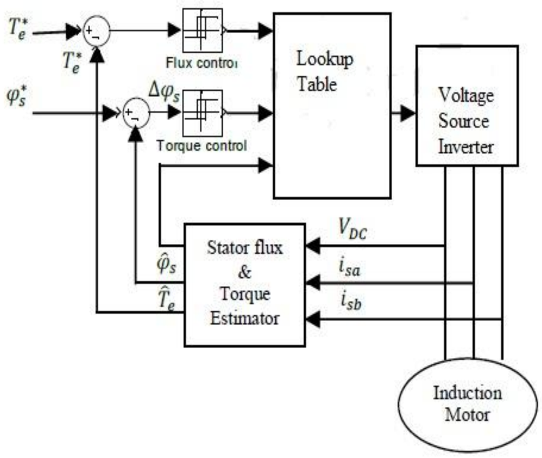

Fig: 1 Diagrammatic representation of Standard DFTC with IM drive

IV. SPACE VECTOR MODULATION BASED DIRECT FLUX AND TORQUE CONTROL

Space vector modulation (SVM) is a vector arrangement of pulse width modulation (PWM) strategy for 3-Ø inverter. It uses full DC bus voltage and thus its output is often more sinusoidal with lower harmonics. In this approach, the 3-Ø quantities are converted into their essential 2-Ø quantities. The magnitude and angle of reference voltage obtained from 2-Ø quantities. The 2-Ø quantities are determined from a d-q axis stator flux reference frame.

The diagrammatic representation of proposed SVM-DFTC technique for an IM drive is as shown in fig.2. In this proposed approach, the hysteresis regulators in standard DFTC have been replaced by PI regulators. Three PI regulators are used in this method. Stator voltage amplitude can be controlled by using the torque PI regulator and flux PI regulator. The reference torque (T_e*) is developed with the help of speed PI regulator and it is possible by using the error data of actual and reference speeds. To reduce the torque and flux ripples, PI regulators used in this method should be properly tuned. By the use of PI regulators, switching frequency can be maintained constant. From the PI regulators the obtained parameters can be represented as follows:

From the flux PI regulator, V_{ds} can be represented as follows:

$$V_{ds} = \left(k_{i\psi} \int \Delta\psi_s dt\right) + k_{p\psi}\left(\Delta\psi_s\right) \tag{11}$$

$$\Delta\psi_s = \psi_{sref} - \psi_{sact} \tag{12}$$

Where ψ_{sact} and ψ_{sref} are the actual and reference values of stator fluxes respectively, $k_{p\psi}$ and $k_{i\psi}$ are proportionality factor and integral factor of flux regulator respectively.

From the torque PI regulator, V_{qs} can be represented as follows:

$$V_{qs} = \left(k_{iT} \int \Delta T_e dt\right) + k_{pT}\left(\Delta T_e\right) \tag{13}$$

$$\Delta T_e = T_{eref} - T_{eact} \tag{14}$$

Where T_{sref} and T_{sact} are the reference and actual values of electromagnetic torque respectively, k_{pT} and k_{iT} are proportionality factor and integral factor of torque regulator respectively.

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From the speed PI regulator, the reference electromagnetic torque $T_e{*}$ can be represented as follows:

$$T_e{*} = \left(k_{i\omega}\int \Delta\omega_{rs}dt\right) + k_{p\omega}(\Delta\omega_{rs}) \qquad (15)$$

$$\Delta\omega_{rs} = \omega_{rsref} - \omega_{rsact} \qquad (16)$$

Where ω_{rsref} and ω_{rsact} are the reference and actual values of rotor speed respectively, $k_{p\omega}$ and $k_{i\omega}$ are proportionality factor and integral factor of speed regulator respectively.

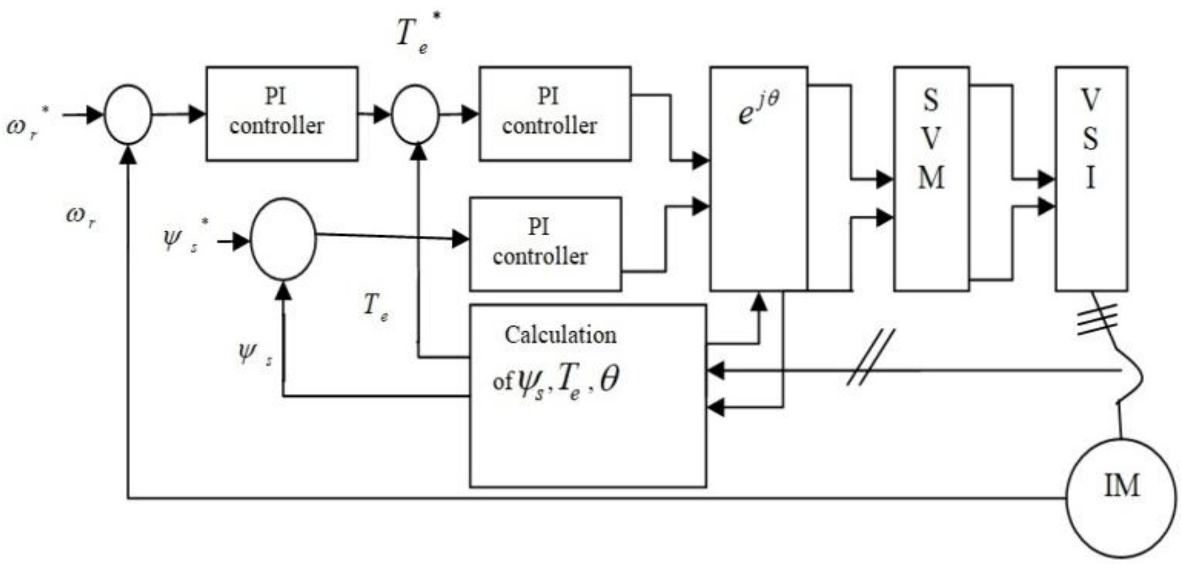

Fig: 2 Diagrammatic representation of proposed SVM-DFTC with IM drive

The vector diagram of the voltage source inverter (VSI) is split into 6 sectors shown in fig.3. 8 vectors are located in 6 sectors in which 2 are zero vectors and 6 are active vectors rotating in the space. The angle between each sector is 60^0. The reference vector begins to rotate in the anticlockwise direction with respect to the motor speed. The reference voltage vector is positioned between two distinct voltage vectors causing changes in its location as sector changes.

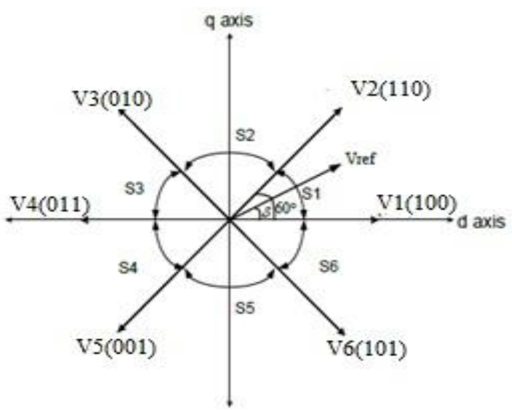

Fig 3.Voltage vector selection in sectors

The magnitude and angle of stator reference voltage vector are indicated as follows:

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$$V_{ref} = \sqrt{V_d^{\,2} + V_q^{\,2}} \qquad (17)$$

$$\theta = \tan^{-1}\frac{V_q}{V_d} \qquad (18)$$

Where V_{ref} is the reference stator voltage magnitude, θ is the reference stator voltage angle.

The magnitude and angle of stator flux can be indicated as follows:

$$\psi_s = \sqrt{\psi_{ds}^{\,2} + \psi_{qs}^{\,2}} \qquad (19)$$

$$\theta = \tan^{-1}\frac{\psi_{qs}}{\psi_{ds}} \qquad (20)$$

Where ψ_s is the reference stator flux magnitude, δ is the of reference stator flux angle.

V. SIMULATION RESULTS

To show the use of proposed SVM-DFTC approach, some simulations are performed for the SVM-DFTC IM drive using MATLAB/SIMULINK software. The induction motor parameters and PI regulators values are shown in the table I.

Figs 4, 5, 6 and 7 represents the Simulink waveforms of electromagnetic torque, rotor speed, and stator flux and stator current of SVM-DFTC based IM drive for the applied load torque of 5 N-m. Based on the simulink waveforms, it is evident that the rotor speed increases from 0 to 0.6 sec due to an electromagnetic torque of 20 N-m produced by the induction motor. The reference electromagnetic torque is also 20 N-m. The actual torque wave follows the reference torque wave with low torque ripples. Owing to the sudden decrement in the electromagnetic torque from 20 N-m to 4 N-m at an interval of 0.6 sec to 0.7 sec, resulting in slight decrement of the speed and this speed will reach the reference speed then the electromagnetic torque settles at 5 N-m. From the fig.5, it is evident that the actual speed wave reaches the reference speed wave with less current ripples. During the process of simulation the stator flux is maintained as 1Wb and the actual flux wave tracks the reference flux wave with very low ripple content. Fig.8 represents the trajectory of stator q-axis and d-axis fluxes and from this, the stator flux trajectory is maintained as circular in nature.

Table I Induction Motor Parameters and PI controller Values

Parameter	Value
Resistance of the stator, R_s	5.51 Ω
Inductance of the stator, L_s	0.3065H
Resistance of the rotor, R_r	4.51 Ω
Inductance of the rotor, L_r	0.3065H
Rotor inertia, J	0.089 $kg.m^2$
Mutual inductance, L_m	0.2919 H
Poles count, p	4
Proportionality factor of speed PI controller, $k_{p\omega}$	2.67
Integral factor of speed PI controller, $k_{i\omega}$	20
Proportionality factor of flux PI controller, $k_{p\psi}$	15000
Integral factor of flux PI controller, $k_{i\psi}$	0.00001
Proportionality factor of torque PI controller, k_{pT}	1000
Integral factor of torque PI controller, k_{iT}	0.00001

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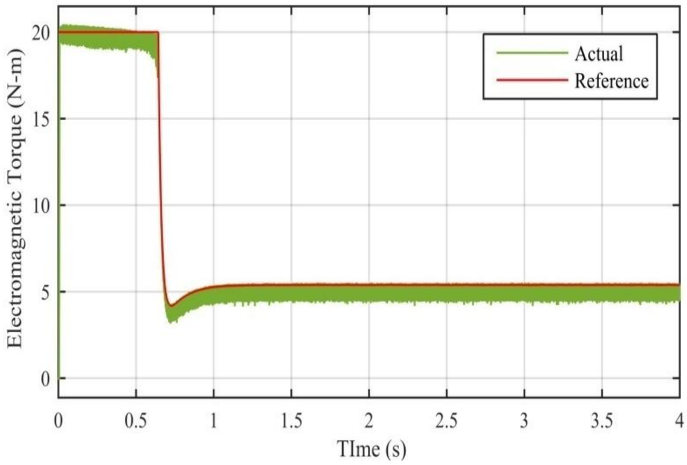

Fig.4. Simulink waveform representation of an electromagnetic torque for SVM-DFTC based IM drive

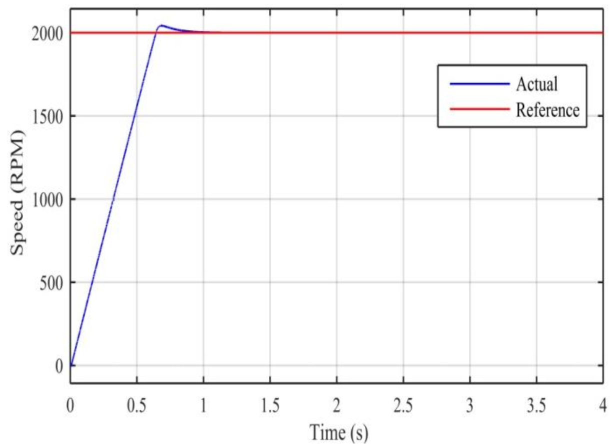

Fig.5. Simulink waveform representation of rotor speed for SVM-DFTC based IM drive

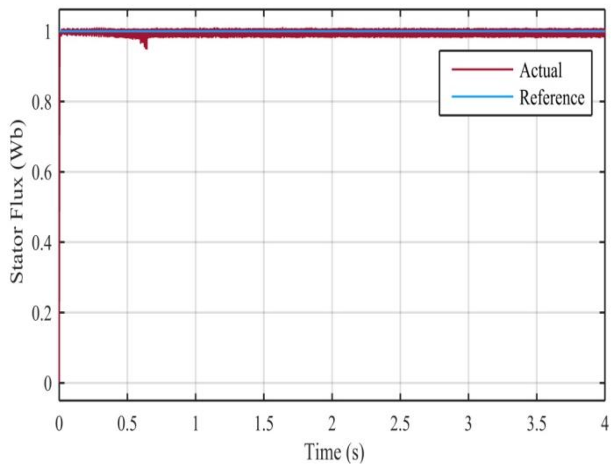

Fig.6. Simulink waveform representation of stator flux for SVM-DFTC based IM drive

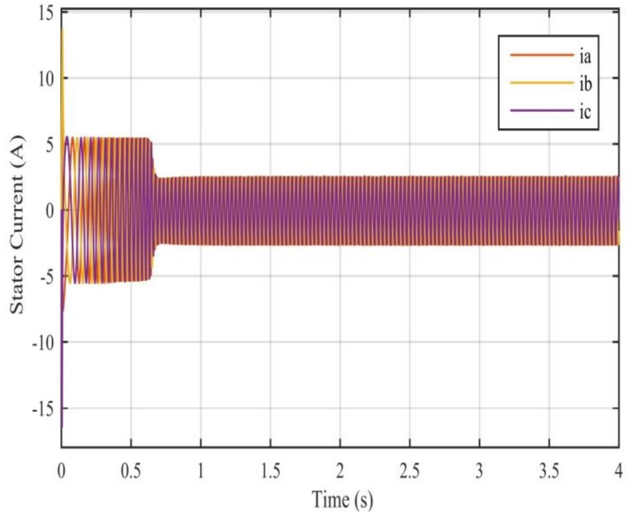

Fig.7. Simulink waveform representation of stator current for SVM-DFTC based IM drive

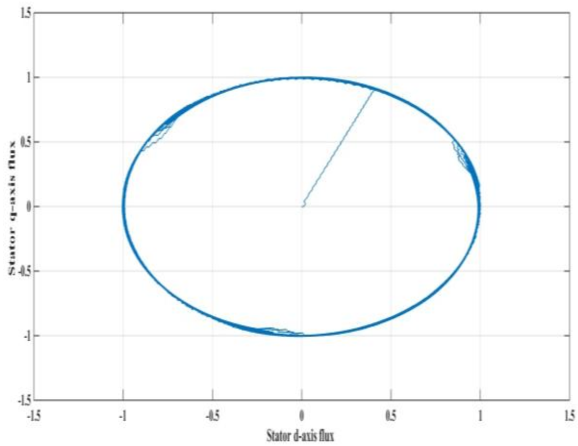

Fig.8. Simulink representation of stator flux trajectory

Figs 9, 10, 11 and 12 represents the Simulink waveforms of electromagnetic torque, rotor speed, and stator flux and stator current of SVM-DFTC based IM drive for the applied load torque of 7 N-m. Based on the simulink waveforms, it is seen that the rotor speed increases from 0 to 0.6 sec due to an electromagnetic torque of 20 N-m produced by the induction motor. The reference electromagnetic torque is also 20 N-m. The actual torque wave follows the reference torque wave with low torque ripples. Owing to the sudden decrement in the electromagnetic torque from 20 N-m to 6 N-m at an interval of 0.6 sec to 0.7 sec, resulting in slight decrement of the speed and this

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speed will reach the reference speed then the electromagnetic torque settles at 7 N-m. From the fig.10, it is evident that the actual speed wave reaches the reference speed wave with less current ripples. During the process of simulation the stator flux is maintained as 1Wb and the actual flux wave tracks the reference flux wave with very low ripple content. Fig.13 represents the trajectory of stator d-axis and q-axis fluxes and from this, the stator flux trajectory is maintained as circular in nature.

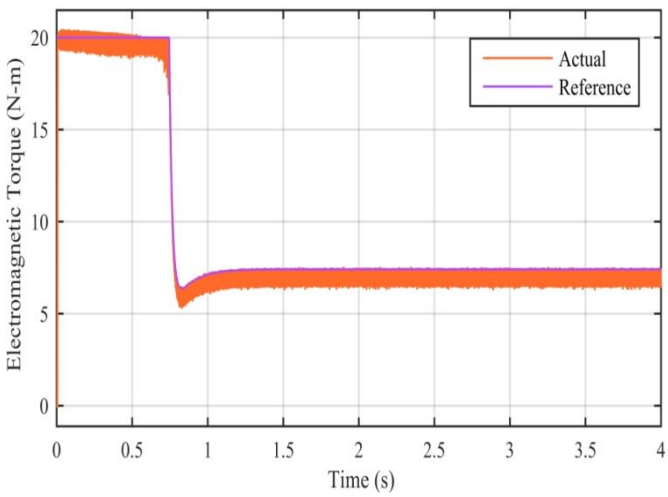

Fig.9. Simulink waveform representation of an electromagnetic torque for SVM-DFTC based IM drive

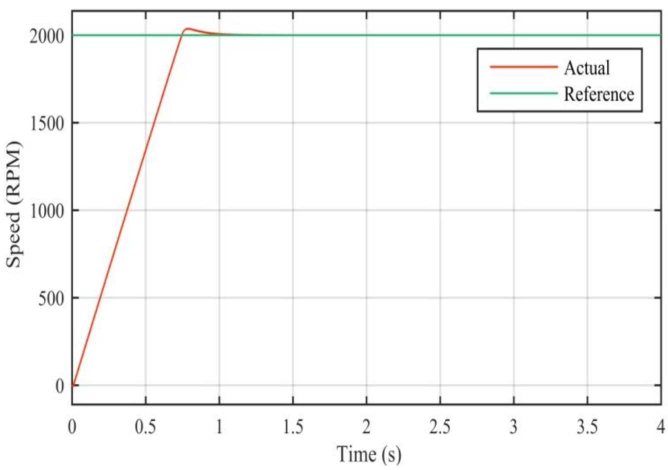

Fig.10. Simulink waveform representation of rotor speed for SVM-DFTC based IM drive

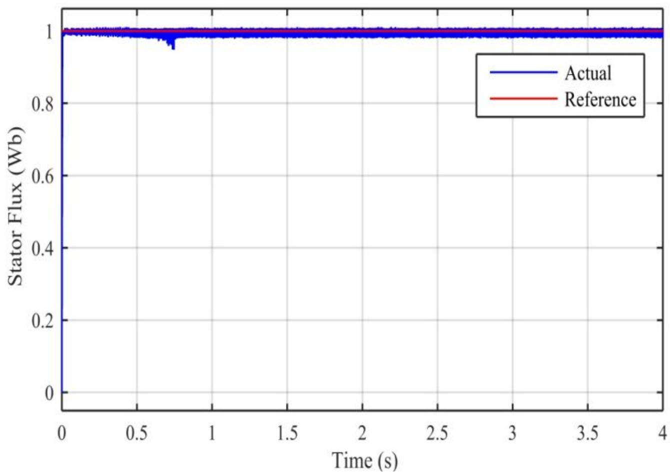

Fig.11. Simulink waveform representation of stator flux for SVM-DFTC based IM drive

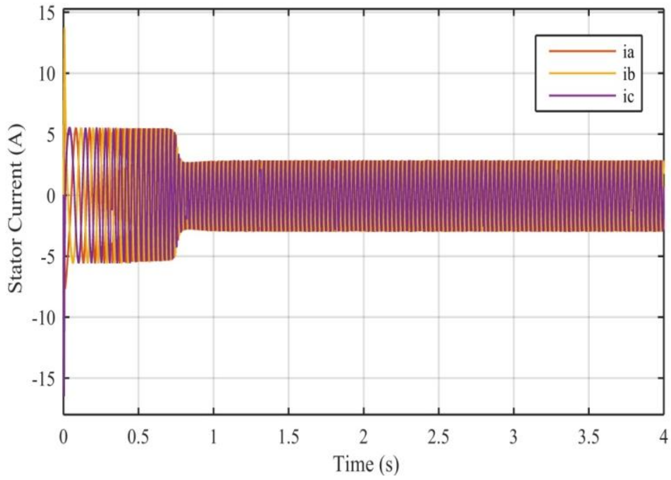

Fig.12. Simulink waveform representation of stator current for SVM-DFTC based IM drive

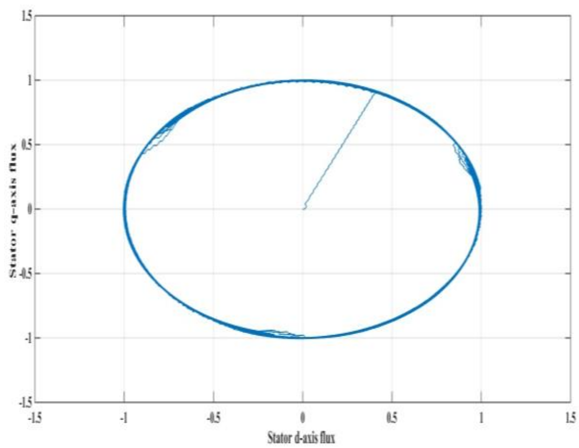

Fig.13. Simulink representation of stator flux trajectory

VI. CONCLUSION

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In this literature, for an induction motor the space vector modulation based direct flux and torque control (SVM-DFTC) approach is implemented. Simulation is conducted with MATLAB/SIMULINK Software. Based on the simulink waveforms of an electromagnetic torque, flux of stator it is evident that the actual values of those quantities is almost as same as the reference values of their corresponding quantities since the actual electromagnetic torque wave follows the reference electromagnetic torque wave and the actual flux wave follows the reference flux wave and also the ripple content for electromagnetic torque is very low. The ripple content in stator current is also decreased. By the inclusion of PI regulators in this technique, constant switching frequency can be obtained. Thus, the SVM-DFTC approach with PI regulator is the best method to control an IM drive.

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