Design and MATLAB Simulation Modelling Using Digital Control System Technique of Direct Torque Control Drive of Three Phase Induction Motor

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Abstract – *This paper presents the Direct Torque Control (DTC) drive scheme for speed control of induction motor using Discrete-Time Integrator technique with MATLAB Simulink. A Direct Quadrate (D-Q) analysis is employed for the mathematical modelling of the DTC, estimation and three phase induction motor based on digital control using MATLAB Simulink. The mathematical model of the 3-phase IM was also studied and simulations were carried out using MATLAB Simulink. The simulation results show that the estimated stator flux angle varies from 0 rad (0^0) to 2π rad (360^0) with an approximate frequency of 50Hz. The steady state estimated stator flux module fluctuates from the reference value with an error of 0.525% maximum ripple. Open loop rotor shaft speed estimation results show that it has good transient and steady state performance with overshoot of 1.531% and with approximated steady state error of 0.0002.*

Keywords*: Backward approximation, direct torque control, Discrete-Time Integrator, Induction motor, MATLAB Simulink*

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I. Introduction

Induction machine is simple, rugged, and considered to be a workhorse of the industry, owing to its numerous high-performance applications [1]. This has made induction motor control drives to dominate the world market. The control of induction motor drives is made possible by a voltage source inverter instead of a 3-phase source comes directly from the mains. This helps to control both electromagnetic torque and stator flux-linkage easily and directly. The inverter gives controlled generated Pulse Width Modulation (PWM) signals of which the amplitude is controlled by a DC link. With this knowledge, it is possible to construct the phase voltages and control the motor's flux linkage and torque. In addition, complicated transformations and calculations such as vector rotation transformations are eliminated. Therefore, the signal processing required by it is particularly simple so as the control signals used to make it possible for the observer to make a direct and explicit determination of the physical process of the AC motor. The stator flux linkage is used for the magnetic field orientation and as long as the stator resistance is known, it can be observed. This greatly reduces the control performance in vector control technology and is susceptible to parameter changes [2]-[3].

DTC technology is divided into two different schemes in terms because the induction motor (IM) is powered by a three-phase symmetrical sine wave, the air gap magnetic potential of the motor is circular [4]. Therefore, the motor losses, torque ripple, and noise are minimal at this location. In many cases, medium and low power applications use the circular flux trajectory scheme; the hexagonal scheme is only used in some high-power applications as switching frequency and switching losses have large limits which are discussed in [5].

The concept of Space Vector Modulation (SVM) has been used to analyze the mathematical model of a three-phase AC motor and control its physical quantity, making the problem particularly simple and clear. This concept is usually employed for the control of PWM to generate alternating current waveforms, especially for 3-phase AC motors [6].

The aim of this paper is to improve the dynamic performance of induction motor drive by providing an efficient model for IM drive using MATLAB Simulink. In addition, the mathematical model of the AC motor has been analyzed directly in the stator coordinate system and equations for the stator flux in the d and q axis have been derived.

II. Methodology

A. Modelling of DTC Drive Using Matlab Simulink

This section describes the modelling approach adopted for direct-quadrature modelling of the DTC for a 3-phase induction motor using MATLAB Simulink. The simulation analysis of the 3-phase squirrel cage induction motor based on DTC drive scheme was performed using the MATLAB Simulink 2016a platform. The model contains the 3-phase induction motor modelled in a stationary reference frame with a rotor speed estimator, stator flux linkage estimation block, stator flux controller, stator flux linkage position identifier block, estimated torque block, torque controller, optimal switching table block, and voltage source inverter. These various parameters can be plotted within a given time interval in seconds. The parameters of the 3-phase induction motor used for modelling the DTC drive are presented in Table I and Table II.

TABLE I
SYSTEM SPECIFICATION OF SQUIRREL CAGE INDUCTION MOTOR

Reference parameter	Values
Rated power (P)	370 W
Stator resistance (R_s)	11.05 Ω
Rotor resistance (R_r)	6.11 Ω
Stator linkage inductance (L_s)	0.316423 H
Rotor linkage inductance (L_r)	0.316423 H
Mutual inductance (L_m)	0.293939 H
Moment of inertia (J)	0.009 kgm^2
Number of poles (p)	4
Stator rated current (i_s)	1.1 A
Rated frequency (f)	50 Hz
Rated electrical(mechanical) rotor speed	2640 (1320) rpm
Rated stator phase rms voltage	220V

TABLE II
BASE VALUES OF VOLTAGE SOURCE INVERTER AND INDUCTION MOTOR

Reference parameter	Values
Base phase voltage	220 V
Base phase current	10 A
Base flux	2.93939 Vs/rad
Base frequency	50 Hz
Base torque	22.604485 N.m
Switching frequency of inverter	10 kHz
Base DC bus voltage	300 V

B. Induction Motor Modelling and Simulation Analysis

Induction machine has nonlinear characteristics by nature. In various studies, it has been shown to have complicated formula when deriving the expression of voltage, current, flux-linkage, and instantaneous electromagnetic torque [7]-[9]. However, by using the fundamental physical laws and space vector theory, it is shown that our derived expression is simplified for the control, design, programming, understanding, and analysis of IM. In addition, the space phasor model gives a detailed explanation of the fundamental principles involved in the analysis of DTC machines [10]-11].

IM dynamic model and equations vary with the type of reference frame used. Stationary reference frames are the most suitable for this analysis as they depend on 3-phase induction motor equivalent circuits in the stationary reference frame. The stationary reference frame dynamic modeling of the 3-phase induction machine is shown in Fig. 1, while the d-q axes is shown in Fig. 2.

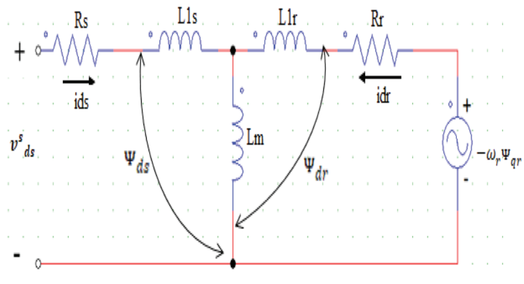


Fig. 1. Equivalent circuit in direct axes referred to as stationary reference frame

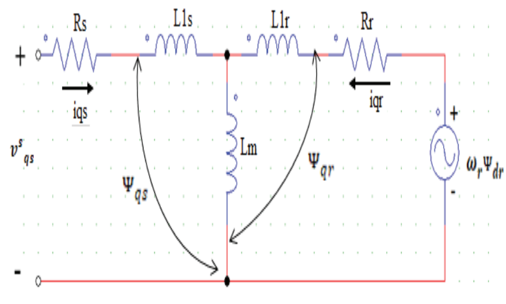


Fig. 2. Equivalent circuit in the quadrature axes referred to as stationary reference frame

Where,

$v^s{}_{d_s}$	voltage in the stationary reference frame in direct axis
$v^s{}_{q_s}$	voltage in the stationary reference frame in quadrature axis
$i^s{}_{ds}$	stationary direct axis current
$i^s{}_{qs}$	stationary quadrature axis current
i_{d_r}	current in the rotor direct reference frame
i_{q_r}	current in the rotor quadrature reference frame
R_s	stator winding resistance
R_r	rotor winding resistance
ψ_{d_s}	direct axis stationary flux linkage
ψ_{qs}	quadrature axis stationary flux linkage
ψ_{d_r}	direct axis rotor flux linkage
ψ_{qr}	quadrature axis rotor flux linkage
$L1r$	linkage rotor winding inductance
$L1s$	linkage stator winding inductance
Lm	mutual inductance
Lr	rotor winding inductance
Ls	stator winding inductance
ω_r	rotor shaft electrical speed
ρ_s	stator flux position
ω_{syn}	synchronous speed

The following equation (1) is derived from the mathematical representation of elements in the equivalent circuits of Fig. 1 and Fig. 2.

$$\left.\begin{aligned} v^s{}_{d_s} &= R_s i_{d_s}(t) + \frac{d\psi_{d_s}(t)}{dt} \\ v^s{}_{q_s} &= R_s i_{q_s}(t) + \frac{d\psi_{q_s}(t)}{dt} \end{aligned}\right\} \quad (1)$$

It is possible to generate another expression for the stator voltage in equation (1) by substituting the stator flux linkage based on the current model given in equations (2) and (3) [12]-[13].

$$\psi_{d_s} = L_s i_{d_s} + L_m i_{d_r} \quad (2)$$

$$\psi_{q_s} = L_s i_{q_s} + L_m i_{q_r} \quad (3)$$

Substituting equations (2) and (3) into equation (1) gives,

$$\left.\begin{aligned} v^s{}_{d_s} &= R_s i_{d_s}(t) + \frac{d}{dt}(L_s i_{d_s} + L_m i_{d_r}) \\ v^s{}_{d_s} &= R_s i_{d_s}(t) + \frac{di_{d_s}(t)}{dt} L_s + L_m \frac{di_{d_r}(t)}{dt} \end{aligned}\right\} \quad (4)$$

$$\left.\begin{aligned} v^s{}_{q_s} &= R_s i_{q_s}(t) + \frac{d}{dt}(L_s i_{q_s} + L_m i_{q_r}) \\ v^s{}_{q_s} &= R_s i_{q_s}(t) + \frac{di_{q_s}(t)}{dt} L_s + L_m \frac{di_{q_r}(t)}{dt} \end{aligned}\right\} \quad (5)$$

By following the same procedure performed in equations (1) to (5), the rotor voltage equation is given as:

$$\left.\begin{aligned} R_r i_{d_r}(t) + L_r \frac{di_{d_r}}{dt} + L_m \frac{i_{d_s}}{dt} + \omega_r(L_r i_{q_r} + L_m i_{q_s}) = 0 \\ R_r i_{q_r}(t) + L_r \frac{di_{q_r}}{dt} + L_m \frac{di_{q_s}}{dt} - \omega_r(L_r i_{d_r} + L_m i_{d_s}) = 0 \end{aligned}\right\} \quad (6)$$

The mechanical equation shows the relationship between speed and torque. This is given as:

$$J\frac{d\omega_m}{dt} = T_{estimated} - T_{load} \quad (7)$$

where ω_r *is* the rotor shaft electrical speed in rad per second, ω_m is the mechanical rotor speed in rad per second. Substituting equations (2) and (3) into the estimated torque equation in equation (11). Finally, we obtained the electrical speed equation as equation (8) assuming load torque is zero.

$$\left.\begin{aligned} &\omega_r = [polepair(pp)]\omega_m \\ &\frac{J}{pp}\frac{d\omega_r}{dt} = \frac{3}{2}pp(i_{q_s}(L_s i_{d_s} + L_m i_{d_r}) - i_{d_s}(L_s i_{q_s} + L_m i_{q_r})) \end{aligned}\right\} \quad (8)$$

The differential equation in equations (4), (5), (6), and (8) are used in the induction machine Matlab Simulink modelling in to obtain the DTC drive performance.

C. Modified Stator Flux Estimator

When working on digital simulation and implementation, the flux linkage equations for both the stator and rotor must be changed from continuous to discrete. In the continuous form of the stator equation, we know that the Laplace term for the derivative is s and $\frac{1}{s}$ is for its integral term. For a digital implementation, we also define the equations based on the types of approximation used, i.e. backward approximation. Therefore, for digital implementation, replace the $\frac{1}{s}$ term (the integral term) with $\frac{1}{s} = \frac{TsZ}{Z-1}$, where s is the continuous Laplace term and Z is the discrete operator, and T_s is the sampling time. By integrating equation (1), equations (9) and (10) are obtained.

$$\psi_{d_s}(t) = \int[v_{d_s}(t) - R_s i_{d_s}(t)]dt \quad (9)$$

$$\psi_{q_s}(t) = \int[v_{q_s}(t) - R_s i_{q_s}(t)]dt \quad (10)$$

Replacing the integral term $\frac{1}{s}$ with $\frac{TsZ}{Z-1}$ for both equations (9) and (10), we obtain the discrete representation form of the stator flux given by equation (11).

$$\left.\begin{aligned} \psi_{q_s} &= T_s(v^s{}_{q_s} - R_s i_{q_s}) + \psi_{q_{s-1}} \\ \psi_{d_s} &= T_s(v^s{}_{d_s} - R_s i_{d_s}) + \psi_{d_{s-1}} \end{aligned}\right\} \quad (11)$$

where $\Psi_{q_{s-1}}$ is the previous value of the stator flux in the q axis, and $\Psi_{d_{s-1}}$ is the previous value of the stator flux in d axis. To get the desired stator flux, a lowpass filter with cutoff frequency of 3 rad/s after performing sampling. This is illustrated in Fig. 3.

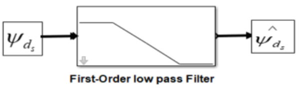


Fig. 3. Low pass filter

The transfer function of the lowpass filter used is $\frac{1}{1+s\tau_c}$, and $\tau_c = \frac{1}{2\pi fc}$ is the suitable time constant used to obtain the stator flux at a low frequency. Backward approximation is used to relate the $\widehat{\Psi_{ds}}$ and Ψ_{ds}, where $\widehat{\Psi_{ds}} = \frac{1}{1+s\tau_c}\Psi_{ds}$ is the output of low pass filter in the stator d axis, and $\widehat{\Psi_{qs}} = \frac{1}{1+s\tau_c}\Psi_{qs}$ is the output of low pass filter in the stator q axis. The designed model for the stator d axis flux is shown in Fig. 4, while that of the stator q is shown in Fig.

5. The Simulink block to calculate the resultant stator flux is shown in Fig. 6, while the stator flux position calculator is shown in Fig. 7.

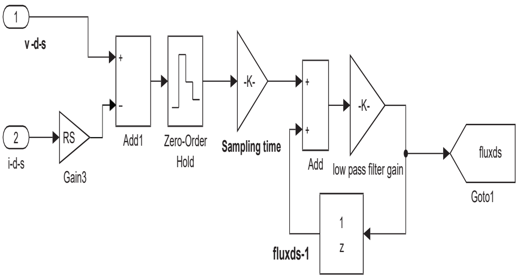


Fig. 4. Digital Simulink block diagram for stator d axis flux in a stationary frame

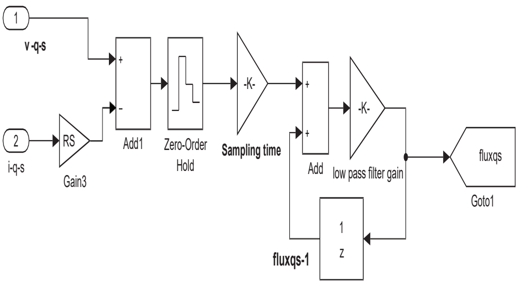


Fig. 5. Digital Simulink block diagram for stator q axis flux in the stationary frame.

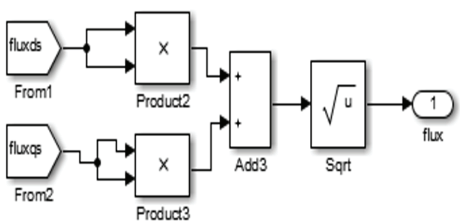


Fig. 6. Resultant Stator flux calculation Simulink block

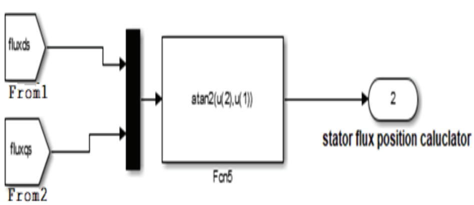


Fig. 7. Flux position Simulink block

D. Modified Torque Estimator

The developed electromagnetic torque can be written as follows in terms of direct and quadrature stator current and stator flux.

$$T_e = \frac{3}{2}\frac{p}{2}(\psi_{d_s} i_{q_s} - \psi_{q_s} i_{d_s}) \qquad (12)$$

This developed torque represented in terms of combination of many other parameters but the selected torque as in equation (12) is measured directly from the sensed parameters so it reduces the burden on the microcontroller during real time implementation.

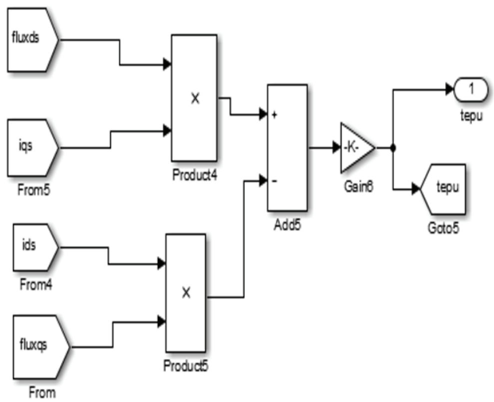


Fig. 8. Torque estimator Simulink block

E. Modified Rotor Speed Estimation Technique

Rotor Speed sensing technique uses its own estimated and measured electrical output parameters like voltage, current, stator flux linkage, rotor flux linkage, and developed torque. Speed estimation of an induction machine is more complex than the synchronous machine due to the slip speed. So, for asynchronous machines, it has many tricks for rotor speed estimation. Various techniques are described which can be used in high-performance drives for the estimation of the synchronous speed, slip speed, rotor speed, rotor angle, and various machine flux linkages [3]. Thus, in this paper, open-loop estimator using monitored stator voltages, currents, and flux linkages is used for the speed estimation.

The main advantages of sensor less-controlled drives are the reduced hardware complexity, the lower cost, the reduced size of the drive machine, the elimination of the sensor cables, the better noise immunity, the increased reliability, and the lower maintenance requirements and lower robustness [4]. The analysis has been done in the stationary reference frame fixed to the stator; the differentiation of stator flux angle gives the synchronous speed as in equation (13).

$$\omega_{syn} = \frac{d\rho_s}{dt} = \frac{d}{dt}\left(a\tan 2\frac{\hat{\psi}_{qs}(t)}{\hat{\psi}_{ds}(t)}\right) \quad (13)$$

Differentiate the above equation using the property of inverse tangent function differentiation.

$$\omega_{syn} = \frac{\hat{\psi}_{d_s}(t)\frac{d}{dt}\hat{\psi}_{q_s}(t) - \hat{\psi}_{q_s}(t)\frac{d}{dt}\hat{\psi}_{d_s}(t)}{\psi_s^2} \quad (14)$$

Equation (14) does not give us the exact estimation rather it gives disturbed higher frequency noise signal due to modeling error [1]. During digital simulation implementation, this can be removed by first order low pass filter as shown in Fig. 9. This paper used a low pass filter with cutoff frequency 5 rad/s. As a result, equations (15) and (16) are derived.

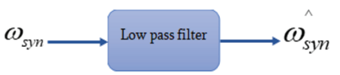


Fig. 9. Low pass filter for synchronous speed estimation

$$\widehat{\omega_{syn}} = \omega_{syn}\frac{1}{1+s\tau_c} \quad (15)$$

$$\hat{\omega}_{syn}\tau_c s + \hat{\omega}_{syn} = \omega_{syn} \quad (16)$$

Using the backward approximation technique, which is one of the analysis in Discrete-Time Integrator, equation (16) can be written as equation (17) by replacing $\frac{1}{s} = \frac{T_s Z}{Z-1}$.

$$\hat{\omega}_{syn} = \omega_{syn}\frac{T_s}{T_s+\tau_c} - \hat{\omega}_{syn_{-1}}\frac{\tau_c}{T_s+\tau_c} \quad (17)$$

The main challenging task during asynchronous machine speed estimation is to obtain slip speed estimation as in equation (18) [1].

$$\omega_{slip} = \frac{2R_r T_{estimated}}{polepair3\psi_r^2} \quad (18)$$

Equation (18) slip estimation technique has simple mathematical analysis and can be easy interims of simulation time and coding from other estimation methods, but it needs resultant rotor flux linkage. So, this rotor flux linkage can be obtained from stator currents and modified estimated stator flux linkage. Also, the main thing in this slip estimation technique, the synchronous speed estimation method is also changed from equation (14). The slip speed is depending on the rotor flux linkage speed [1]. Then the rotor speed is estimated as follows.

$$\omega_r = \hat{\omega}_{syn} - \omega_{slip} \quad (19)$$

Fig. 10 shows the overall system block diagram of the 3-phase induction motor with Direct Torque Control drive scheme based on the Matlab Simulink model.

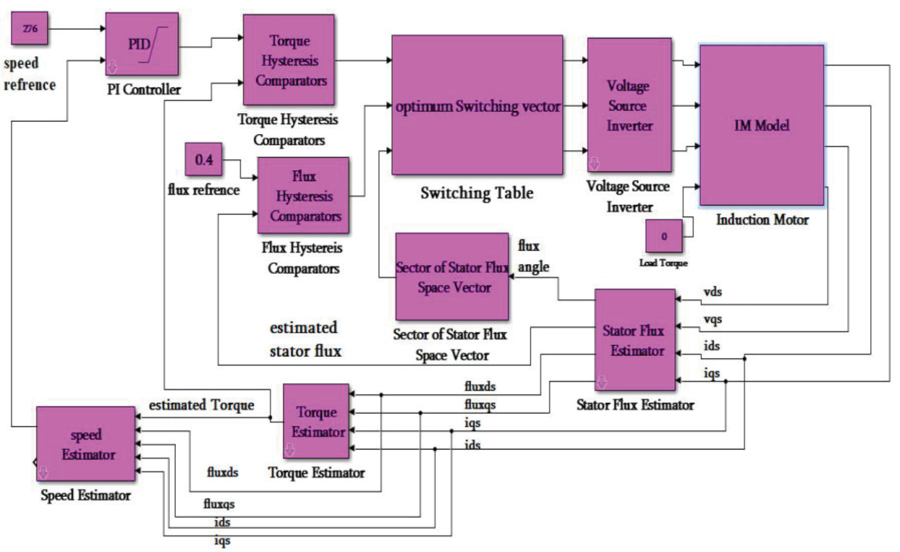


Fig. 10. overall system block diagram of the 3-phase induction motor with Direct Torque Control drive scheme based on the Matlab Simulink model

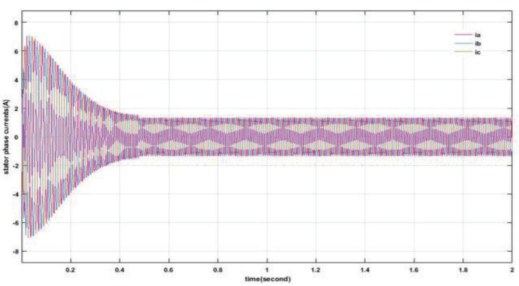
III. Results of Simulation

The simulation results obtained with MATLAB Simulink are shown in Fig. xx to Fig. xx. The Simulink block in MATLAB generally has the DTC IM drive with a closed-loop speed control system using an estimated speed as feedback. This is compared with the reference speed using a PI as a speed controller. The reference values for the different parameters are presented in Table III.

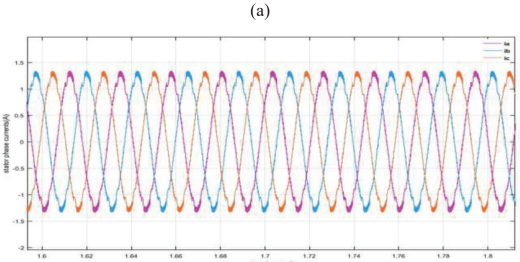
TABLE III
SET POINT VALUES OF DIFFERENT PARAMETERS USED IN THE SIMULATION

Reference parameters	Values
Stator flux	0.4 volt-sec/rad
Rotor electrical speed reference	276 rad/sec
K_P	50
K_I	0.03
V_{dc} (DC bus voltage)	200V

The following Fig. 11(a) shows that initially the stator phase current has a large value which is observed from the high gain of the PI controller. This value is seen to reduce when it reaches a steady state. Also, it is observed that in (b), the 3-phase stator winding current has approximately sinusoidal waveforms with constant frequency.



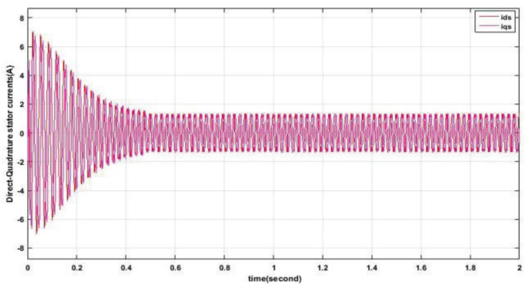
(a)



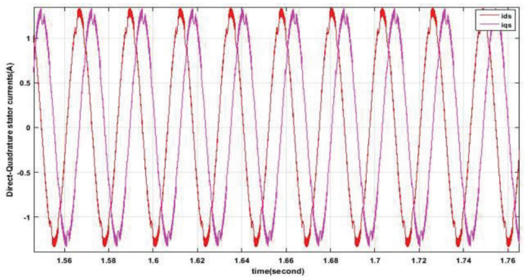
(b)

Fig. 11. Results of Stator 3-phase currents for Phase A, Phase B, and Phase C using MATLAB Simulink

The simulation results of the direct and quadrature axis currents are shown in Fig. 12; the direct axis current is almost the same as the stator phase A current. Fig. 12(b) shows that the angle between the direct and quadrature stator current has a 90^0 phase shifts as expected. A similar phase shift is also observed in the direct and quadrature axis stator flux in Fig. 13.

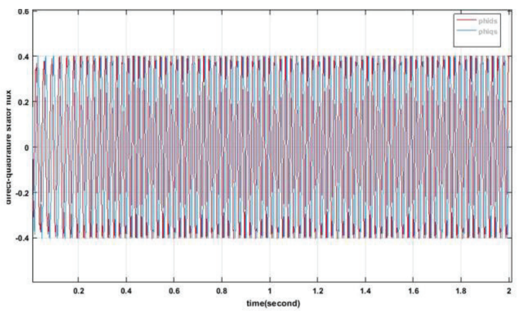


(a)

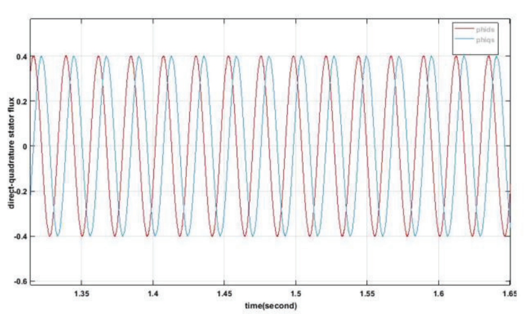


(b)

Fig. 12. Stationary axis stator current Direct, and Quadrature



(a)



(b)

Fig. 13. Stationary axis stator flux Direct, and Quadrature

A number of authors have stated that synchronous speed frequency is approximately 50Hz and that the stator flux linkage is directly influenced by the synchronous speed frequency [14]. An approximated frequency of 50Hz was obtained as observed in Fig. 13. The flux locus in Fig. 14 indicates that it plots the flux of the direct axis (horizontal) versus the quadrature axis (vertical). The locus must be maintained at a reference flux, otherwise the flux estimation technique is not proper. Fig. 15 shows that the resultant stator flux values are kept constant throughout the running time and a maximum relative error of 0.525% is achieved. This error emanates as a result of the presence of ripples in our estimation.

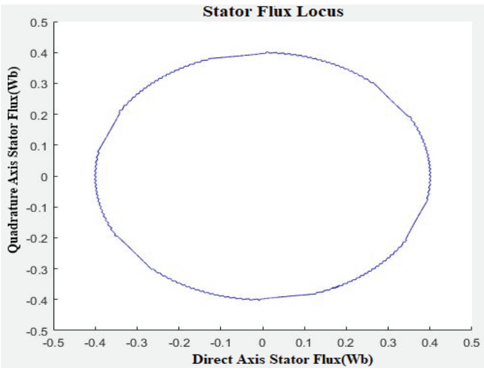


Fig. 14. Stator flux locus Steady-state flux locus

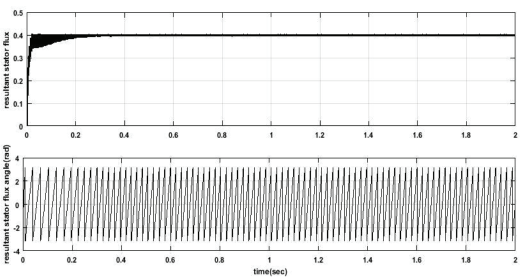
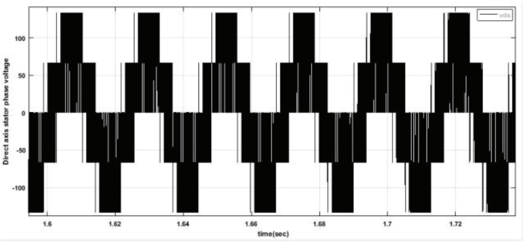
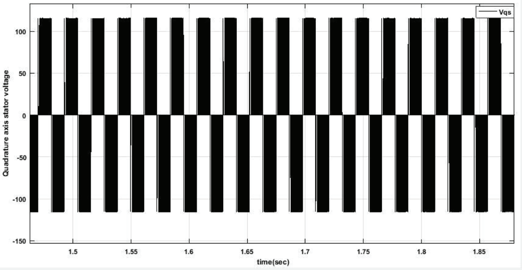


Fig. 15. Estimated stator flux modulus and estimated stator flux angle

Estimation of the stator flux angle shows that it varies from 0 rad (0^0) to $2\pi\, rad$ (360^0) with an approximate frequency of 50Hz. Arc tangent (atan2) function returns the value from $-\pi$ to π, which covers all quadrants. In Fig. 16, the results of the direct axis stator voltage and quadrature axis stator voltage with sampling time of 0.02s are shown. The results show a constant flow of the *d-q* axis phase voltage as compared to conventional DTC models [15]-[16]. The open loop speed estimation technique in this paper attains a fast transient and steady state speed response with a given reference value of 276 rad/s as shown in Fig. 17. Furthermore, the slip speed estimation techniques used in this paper has high accuracy as shown in the figure. At steady state, the rotor speed however has some fluctuation due to the torque ripple, which can be reduced using modern torque and speed estimation techniques such as fuzzy logic and neural network.



(a)



(b)

Fig. 16. Phase voltage in the stationary *d-q* axis

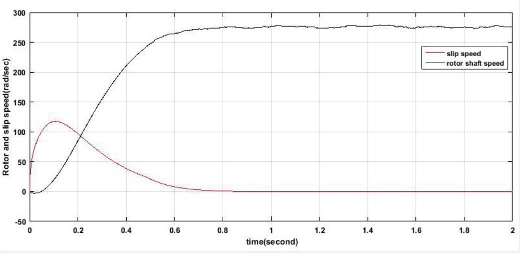


Fig. 17. Estimated rotor speed

IV. Conclusion

In this paper, the simulation of open loop speed control of 3-phase induction motor with PI controller has been carried out. Rotor shaft speed is estimated from the estimated torque and flux of the motor. The results show that the developed *d-q* model of the DTC gave an improved steady state performance and thus can be used in high performance motor drive systems such as field-oriented control of induction motor, and sensorless speed control of induction motor. These types of modeling can be used for implementation purpose by using digital signal processing microcontroller.

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