

Simulation of an Indirect Rotor Flux Oriented Induction Motor Drive Using Matlab/Simulink

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ABSTRACT

Indirect Field Oriented Control (IFOC) is very popular technique in industries due to its simple designing and structure, in comparison to the direct method since it requires flux and torque estimators. This paper presents detail calculation of all values needed for the development of an indirect rotor flux oriented induction motor model fed by a current-controlled voltage source inverter. With the calculated values for 1 hp 50 Hz 3 phase induction motor; an indirect rotor flux oriented model is developed using MATLAB/Simulink. The simulation results are outlined and discussed.

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1. INTRODUCTION

Induction motors find their wide use in industries and homemade applications as it possesses several advantages. Despite of various advantages, control of an induction motor is difficult in comparison to the DC machines because in DC machine, field and armature fluxes are 90° apart, they do not interact with each other and hence flux of the DC motor can be controlled by field current and torque by armature current. However, in case of induction motor, stator and rotor fluxes interact with each other due to non orthogonal and varying orientations. Hence independent control of flux and torque is difficult. However the difficulty in control of Induction motor has been removed by the introduction of several control techniques viz. Scalar Control, Vector or Field Oriented Control, Direct torque control etc. [1]-[6]. The Vector or Field Oriented Control (FOC) was introduced by Blaschke in 1972. With this strategy, IMs can be controlled like a DC machine by maintaining a fixed orthogonal orientation between two fields.

Field Oriented Control can be implemented in three field or flux orientations as there are three flux linkages available in an Induction motor. They are- stator, air gap & rotor flux linkage. Rotor Flux Orientation is a technique that provides a method of decoupling the stator currents of squirrel-cage induction motor in to two components in the synchronously rotating reference frame (d-q frame):- one, the magnetizing current i_{ds}^* , which is to excite the motor flux and the other torque current i_{qs}^* , which is to generate the electromagnetic torque respectively. Therefore, it provides independent control of torque and flux, which is similar to a separately excited DC machine. Basically, there are two methods of Field Oriented control based on the way of determining the rotor angle - Direct method proposed by Blaschke in which rotor angle is obtained by the terminal voltages and currents and Indirect method proposed by Hasse in which rotor angle is

obtained by rotor position measurement and machine parameters [7],[8]. Rotor flux orientation (RFO) is the original and usual choice for the indirect field oriented control . Hence the name Indirect Rotor Flux orientation.

The Field Oriented Control technique needs more calculations than the other control methods. The main contribution of this paper is to compute all the values needed for the implementation of indirect rotor field oriented control, viz. parameters of the motor, the rated rotor flux, the rated stator d-axis and q-axis rms and peak values of currents and the value of the slip speed for rated torque operation, selection of the DC voltage etc [9],[10],[11]. It is also necessary to determine the parameters of the speed PI controller-Kp & Ki.

This paper is organized as follows: Section 2 presents the calculations for parameter determination of the Induction motor under test, Section 3 describes the calculations required for design of Indirect Rotor Flux orientation control scheme. Section 4 present the SIMULINK model development for Indirect Rotor Flux oriented Induction motor using MATLAB. In section 5 simulation results & discussions are presented and the paper ends with the conclusion.

2. CALCULATIONS FOR PARAMETER DETERMINATION

Determining the parameters of Induction Machines is very important step while considering Field Control Technique. The parameters of the induction motor are determined by performing no-load and blocked rotor test [12]. The name plate data of the induction motor under test is mentioned in Table 1.

Table 1 Name plate data of Induction Motor under test

Nominal Power (Watts)	Voltage (line-to-line) (Volts)	Frequency (Hertz)	Inertia (Kg.m ²)	Friction factor (N.m.s)	No.of pole pairs	Speed (rpm)	Rated Current (Amp)
Pn	Vn	fn	J	F	p	Nn	Isn
750	415	50	0.005776	0.00328	2	1490	2

The results of the no-load and blocked rotor tests on 1 hp, three-phase, 415V, four-pole, 50 Hz, Squirrel-cage induction motor are given in Table 2 and Table 3

Table 2 No-load Test data

Line to line Voltage (Volts)	Line Current (Amp)	Input Power (watts)	Speed (rpm)	Frequency (Hertz)
Vnl	Inl	Pnl	Nnl	Fnl
412	1.4	144	1497	50

Table 3 Blocked Rotor test data

Line to line Voltage (Volts)	Line Current (Amp)	Input Power (watts)	Speed (rpm)	Frequency (Hertz)
Vbr	Ibr	Pbr	Nbr	Fnl
140	2.58	386	0	50

Stator resistance 9.395Ω per phase. From No-load test data, following parameters are computed. No load Voltage per phase:

$$V_{ph} = \frac{V_{nl}}{\sqrt{3}} \quad (1)$$

No load Power per phase:

$$P_{ph} = \frac{P_{nl}}{3} \quad (2)$$

No-load power factor:

$$\cos\phi_{nl} = \frac{P_{ph}}{V_{ph} * I_{nl}} \quad (3)$$

Magnetising current:

$$I_m = I_{nl} * \sin(\phi_{nl}) \quad (4)$$

Core loss current:

$$I_c = I_{nl} * \cos(\phi_{nl}) \quad (5)$$

Magnetising or Mutual Inductance:

$$L_m = \frac{V_{ph}}{2\pi f_{nl} * I_m} \quad (6)$$

From Blocked rotor test data, following parameters are calculated-

Short circuit voltage per phase:

$$V_{scph} = \frac{V_{br}}{\sqrt{3}} \quad (7)$$

Short circuit power per phase:

$$P_{scph} = \frac{P_{br}}{3} \quad (8)$$

Short circuit power factor:

$$\cos\phi_{sc} = \frac{P_{scph}}{V_{scph} * I_{br}} \quad (9)$$

Short circuit impedance:

$$Z_{sc} = \frac{V_{scph}}{I_{br}} \quad (10)$$

Rotor resistance:

$$R_r = Z_{sc} * \cos(\phi_{sc}) - R_s \quad (11)$$

Equivalent reactance:

$$X_{eq} = Z_{sc} * \sin(\phi_{sc}) = X_{ls} + X_{lr}' \quad (12)$$

Where X_{ls} = Stator leakage reactance

X_{lr}' = Rotor leakage reactance as referred to stator

The connection between X_{ls} and X_{lr}' for the most common types of industrial Induction motors grouped by the National Electrical Manufacturer's Association (NEMA) is shown in Table 4.[11]

Table 4. NEMA Class motor classifications

NEMA Class	Connection
Class A and D	$X_{ls}=X_{lr}'$
Class B	$X_{ls}=(2/3)X_{lr}'$
Class C	$X_{ls}=(3/7)X_{lr}'$

Since most of the general purpose motors are Nema class B, for Nema Class B Induction motors, Stator Leakage Reactance:

$$X_{ls}=0.4 * X_{eq} \quad (13)$$

Rotor Leakage Reactance as referred to stator:

$$X_{lr}'=0.6 * X_{eq} \quad (14)$$

A .m file is created containing all the data mentioned in Table 1 to Table 3 and all the formulas represented by (1) to (14) to calculate the parameters of the Induction motor. Thus the calculated parameters of the induction motor under test are tabulated in Table 5.

Table 5.Parameters of Three Phase Induction Motor

Stator Resistance (Ohm)	Stator Leakage inductance (Henry)	Rotor Resistance (Ohm)	Rotor Leakage inductance (Henry)	Mutual Inductance (Henry)
R_s	L_{ls}	R_{r}'	L_{lr}'	L_m
9.395	0.0350	10.444	0.0525	0.5492

3. PROPOSED METHODOLOGY AND ITS DESIGN

The vector control technique chosen here is an indirect rotor flux orientation. The basic principle of the indirect rotor field oriented control scheme of an induction motor is to lock the rotor flux vector with d-q co-ordinate reference frame. These results in decoupling of stator currents which controls the flux and the torque separately by controlling stator direct axis current i_{ds} and stator quadrature axis current, i_{qs} respectively like a separately excited DC machine. Locking of d-q co-ordinate reference frame revolving with rotor flux needs the information about the magnitude and the position of the rotor flux. Fig.1 shows the block diagram of the Indirect Rotor Field oriented control scheme. The torque producing component of the stator current, i_{qs}^* is:

$$i_{qs}^* = \left(\frac{2}{3}\right) \left(\frac{2}{P}\right) \left(\frac{L_r}{L_m}\right) \frac{T_e^*}{|\psi_r|_{est}} \quad (15)$$

where L_r is the rotor inductance, L_m is the mutual inductance, and $|\psi_r|_{est}$ is the estimated rotor flux linkage given by:

$$|\Psi_r|_{est} = \frac{L_m}{1 + \tau_r s} . i_d \quad (16)$$

where $\tau_r = L_r / R_r$ is the rotor time constant.

The flux producing component of stator current i_{ds}^* is:

$$i_{ds}^* = \frac{|\Psi_r|_{est}^*}{L_m} \quad (17)$$

The rotor flux position θ required for coordinates transformation is

$$\theta = \int(\omega_e + \omega_{sl})dt. \quad (18)$$

The slip frequency ω_{sl} is:

$$\omega_{sl} = \frac{L_m}{|\Psi_r|} \frac{R_r}{L_r} i_{qs} \quad (19)$$

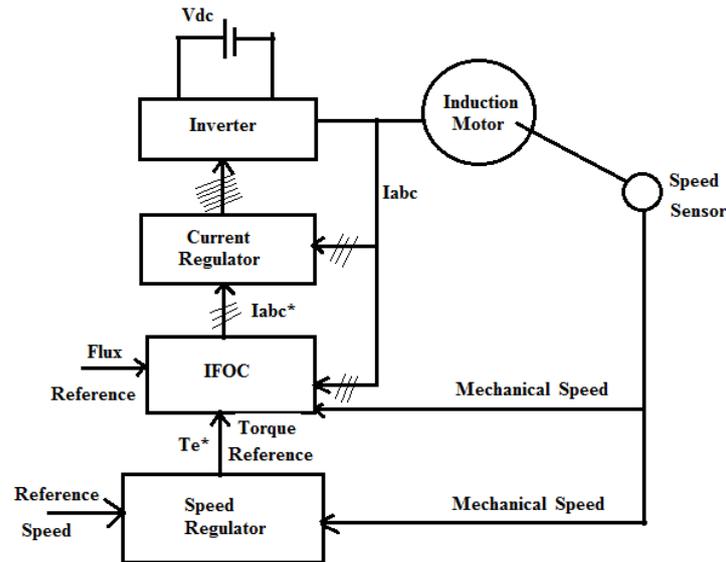


Figure 1 Block diagram of Indirect Rotor Field Oriented Control Scheme

The q and d-axis voltages in synchronous reference frame are [3] given by:

$$V_{qs} = \frac{V_n^* \sqrt{2}}{\sqrt{3}} \quad (20)$$

$$V_{ds} = 0 \quad (21)$$

The induction motor model in electrical synchronous reference frame is given by:

$$V_{qs} = (R_s + L_s p) i_{qs} + \omega_s L_s i_{ds} + L_m p i_{qr} + \omega_s L_m i_{dr} \quad (22)$$

$$V_{ds} = -\omega_s L_s i_{qs} + (R_s + L_s p) i_{ds} - \omega_s L_m i_{qr} + L_m p i_{dr} \quad (23)$$

$$V_{qr} = L_m p i_{qs} + (\omega_s - \omega_r) L_m i_{ds} + (R_r + L_r p) i_{qr} + (\omega_s - \omega_r) L_r i_{dr} \quad (24)$$

$$V_{dr} = -(\omega_s - \omega_r) L_m i_{qs} + L_m p i_{ds} + (\omega_s - \omega_r) L_r i_{qr} + (R_r + L_r p) i_{dr} \quad (25)$$

The steady state currents are thus evaluated by using synchronous reference frame equations with the substitution of $p=0$ and the slip speed being zero. The stator and rotor flux linkages in electrical synchronous reference frame are given by:

$$\Psi_{qs} = L_s i_{qs} + L_m i_{qr} \quad (26)$$

$$\Psi_{ds} = L_s i_{ds} + L_m i_{dr} \quad (27)$$

$$\psi_{qr} = L_r i_{qr} + L_m i_{qs} \quad (28)$$

$$\psi_{dr} = L_r i_{dr} + L_m i_{ds} \quad (29)$$

Substituting the corresponding values, the resultant stator & rotor fluxes are given by:

$$\Psi_s = \sqrt{\Psi_{qs}^2 + \Psi_{ds}^2} \quad (30)$$

$$\Psi_{rated} = \sqrt{\Psi_{qr}^2 + \Psi_{dr}^2} \quad (31)$$

3.1 Calculation of Rated Torque

Under no-load & rated condition, rated torque is given by:

$$T_L = T_e = T_{sh} = P_n / \omega_n \approx 5 \text{ N-m.} \quad (32)$$

All the above formulas from (15) to (32) are included in the earlier created .m file and the commanded values of voltages, currents and fluxes are computed.

3.2 Speed Controller

The most commonly used controller for the speed control of induction motors is conventional PI controller. The transfer function of PI controller is given by:

$$G_c(s) = \frac{K_p s + K_i}{s} \quad (33)$$

Proportional gain and the integral gain, K_p & K_i , are the parameters of PI controller. These parameters are determined using manual tuning technique. In manual tuning process, initially K_p was kept equal to 1 & K_i equal to 0.0001. Then, K_p was increased till the output shows some oscillations. Then K_i was changed to remove steady state error.

3.3 Selection of Dc Voltage (V_{DC}):

The induction motor is fed by a current-controlled PWM inverter which has 2- voltage levels. For a 2-level voltage, line-to-line voltage is: $V_{L-L} = 0.612 * m_{index} * V_{dc}$

Since modulation index ≤ 1 , DC link voltage is:

$$V_{DC} \geq \frac{V_{L-L}}{0.612} \quad (34)$$

So the inverter is built with $V_{dc} = 700$ Volts.

4. DEVELOPMENT OF SIMULINK MODEL

Based on the equations presented in the section 3 and using various tool boxes available in the SIMULINK library, model is developed for each block. Step by step development of model is presented here.

4.1 Speed Regulator Block

As mentioned in section 3.2, the commonly used speed regulator is conventional PI controller. The simulink model of it is implemented as shown Figure.2.

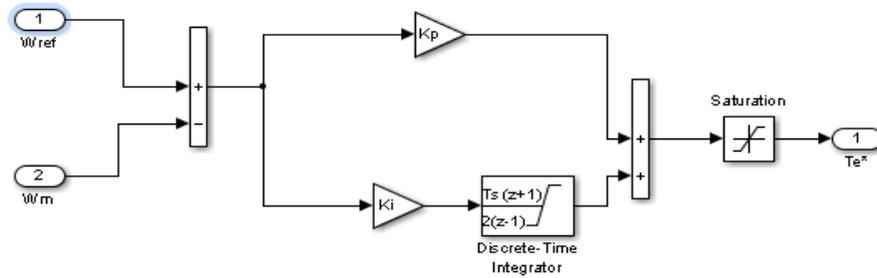


Figure 2 Simulink model of Speed PI controller

4.2 IFOC Block

This block is implemented as shown in Figure 3. It consists of 7 main sub-blocks: Ids* computation, Iqs*

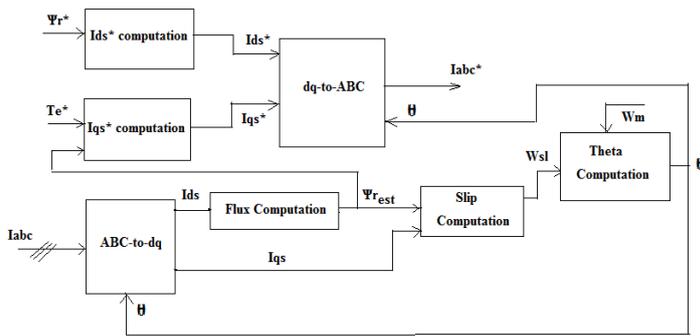


Figure 3 Simulink model of IFOC

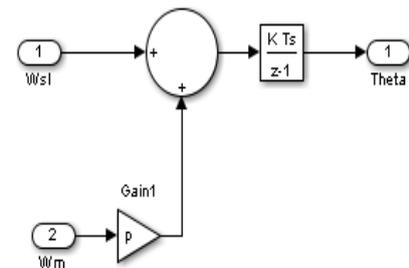


Figure 4 Simulink model of Theta Computation

computation, ABC-to-dq transformation, dq-to-ABC transformation, Flux computation, Slip computation and Theta computation blocks. Simulink model of some of these blocks are presented in the following subsection. Based on (18), Simulink model of this block is implemented as shown in Figure 4.

4.2.1 ABC-TO-DQ Transformation

This transformation is called as Park’s transformation. A Simulink model is developed based on the (35).

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \gamma) & \cos(\theta + \gamma) \\ -\sin(\theta) & -\sin(\theta - \gamma) & -\sin(\theta + \gamma) \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{35}$$

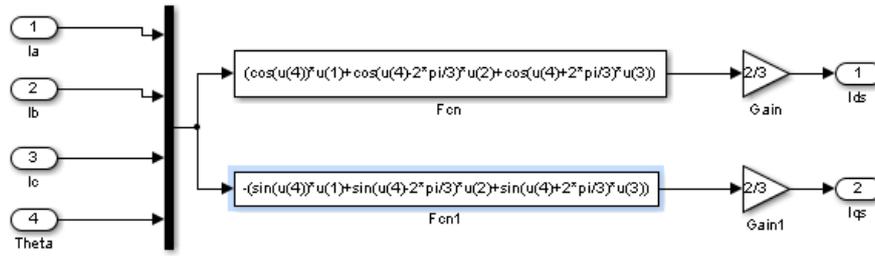


Figure 6 Simulink model of ABC-to-dq transformation

4.2.2 DQ-TO-ABC Transformation

This transformation is called as Inverse Clarke’s transformation. A Simulink model is developed based on (36).

$$\begin{bmatrix} I_a^* \\ I_b^* \\ I_c^* \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \cos(\theta - \gamma) & -\sin(\theta - \gamma) \\ \cos(\theta + \gamma) & -\sin(\theta + \gamma) \end{bmatrix} \begin{bmatrix} I_d^* \\ I_q^* \end{bmatrix} \quad \text{where } \gamma=2\pi/3 \quad (36)$$

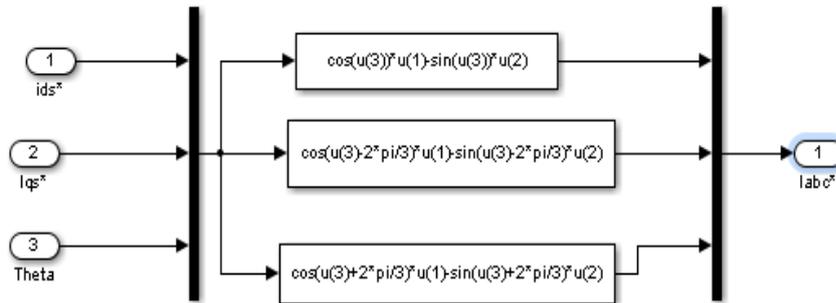


Figure 7 Simulink model of dq-to- ABC transformation

4.3 Current Regulation

Current regulator used in this field oriented control is hysteresis band current controller. It is one of the several types of PWM techniques. It is basically a feedback current control method of PWM where the actual currents are compared with the reference currents within the specified hysteresis band. Thus the inputs to the Hysteresis controller are three phase current errors and the outputs are the switching pulses to the inverter. Fig.8 below shows the Simulink model of Hysteresis current controller. Simulink model for other blocks viz. Iqs* Computation, Flux computation and Ids* computation are implemented as per (15) to (36). Fig.9 shows the complete simulink model of the indirect rotor field oriented Induction motor which is now ready for simulation.

5. SIMULATION RESULTS AND DISCUSSION

Before starting the simulation, a .m file prepared earlier is executed at the Matlab prompt so that all the values of the variables in the Simulink model will be assigned to them. A switching frequency of inverter is taken as 20KHz and a DC link voltage is taken as 700 V.

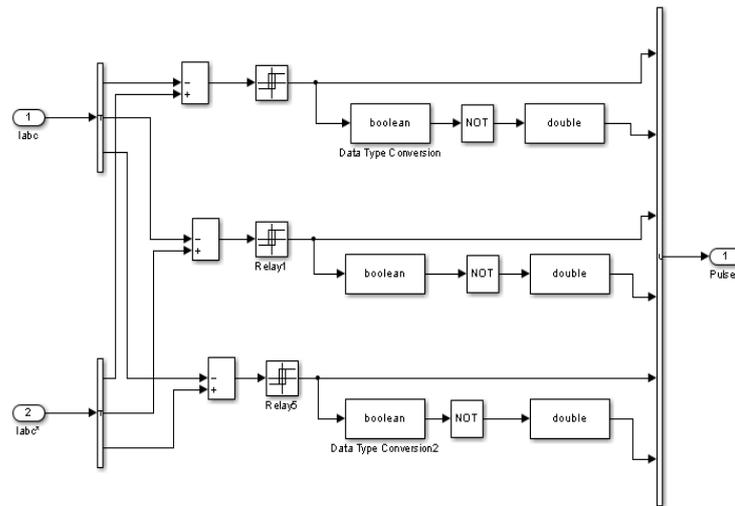


Figure 8 Hysteresis Band current regulator

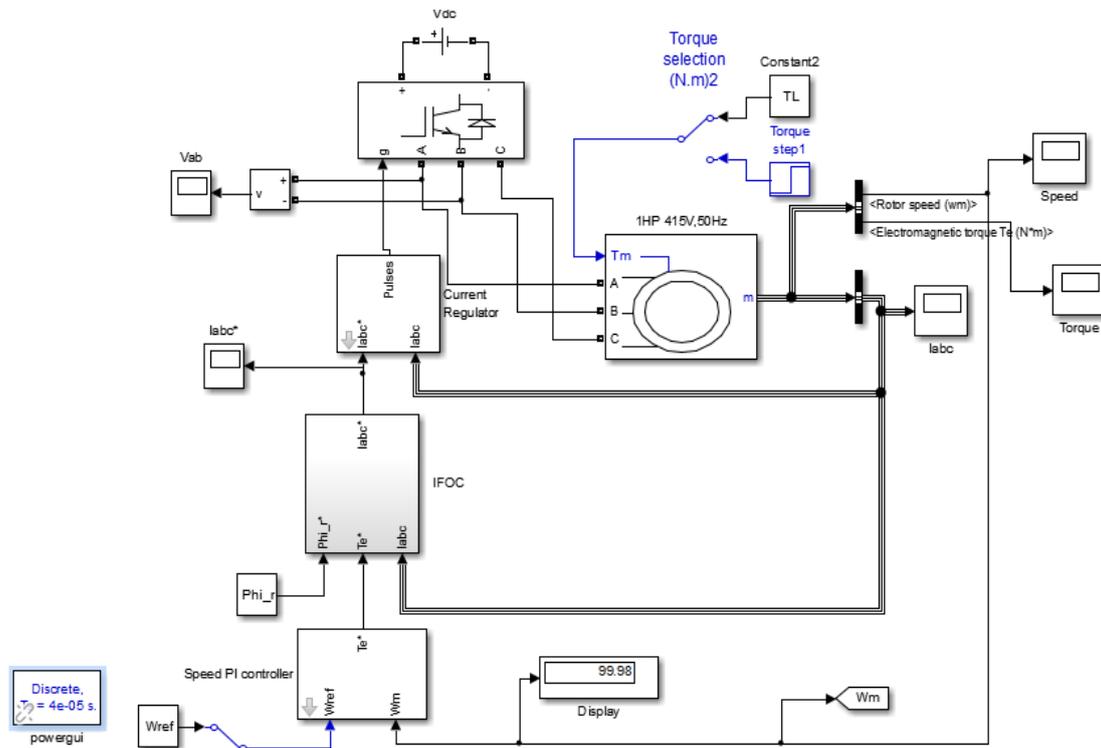


Figure 9 Simulink model of Indirect Rotor Field Oriented Induction Motor

Initially the reference speed is set to a constant value of 100 rad/s (955rpm) and the load torque is also kept constant at 0 N-m. Setting the correct parameters of the speed PI controller and hysteresis band is an important task in simulating the model for getting the accurate results. The values of K_p , K_i and hysteresis band are to be adjusted number of times and simulation is run every time until accurate results are obtained. There are many frequency domain and time domain methods available for designing of a PI controller including the most popular Ziegler-Nichols method of tuning PID controller. But all these methods do not guarantee that the controller parameters found by them gives you accurate performance

characteristics. They just give the initial guess for the controller parameters and finally you have to tune the controller manually.

Here the speed PI controller is tuned manually. The simulation is run for the 3 sec and the responses are observed on the respective scopes. The response curves of Rotor speed, electromagnetic torque (T_e^*), flux, stator current (I_{abc}) vs time are observed and are shown in Figure 10 to Figure13. Figures on the left hand side are for $K_p=1$, $K_i=0.001$ and $h=1$ whereas those on right hand side are for $K_p=4$, $K_i=0.15$ and $h=0.006$. After comparing the figures on the left hand side with right hand side, it is cleared that due to improper selection of PI controller parameters, speed is not reaching to the set speed and hence the flux is also not reaching to the calculated value of 1.012 Wb. Moreover due to improper selection of hysteresis band width h , disturbance in the torque and stator currents are clearly observed. Simulations are carried out for various reference speeds.

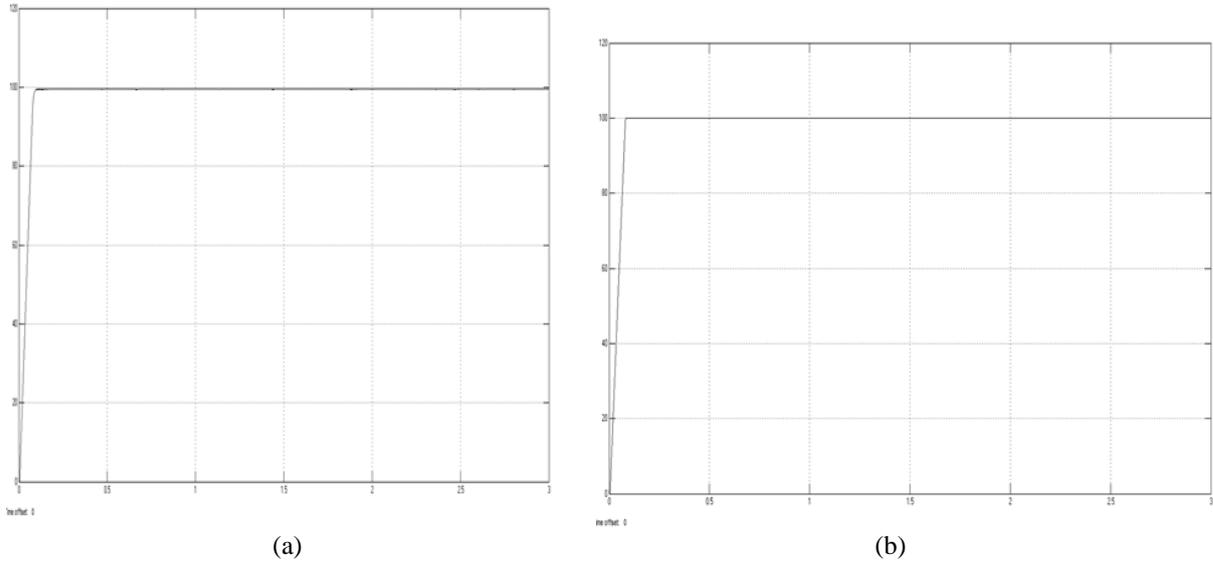


Figure10 Rotor Speed vs Time

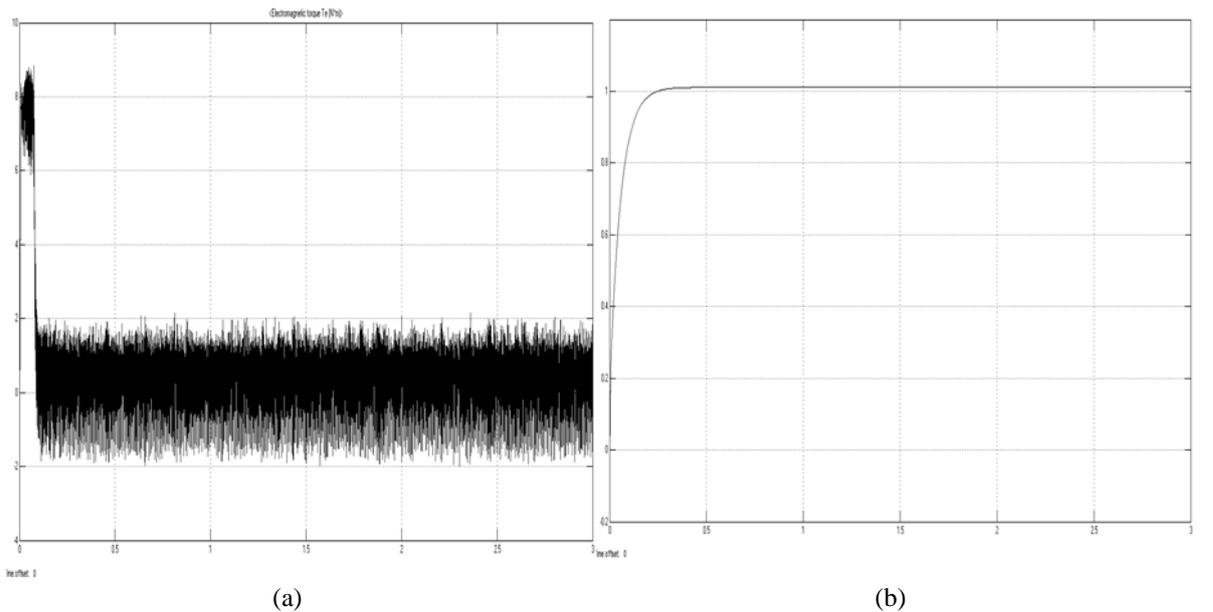


Figure 11 Electromagnetic Torque vs time

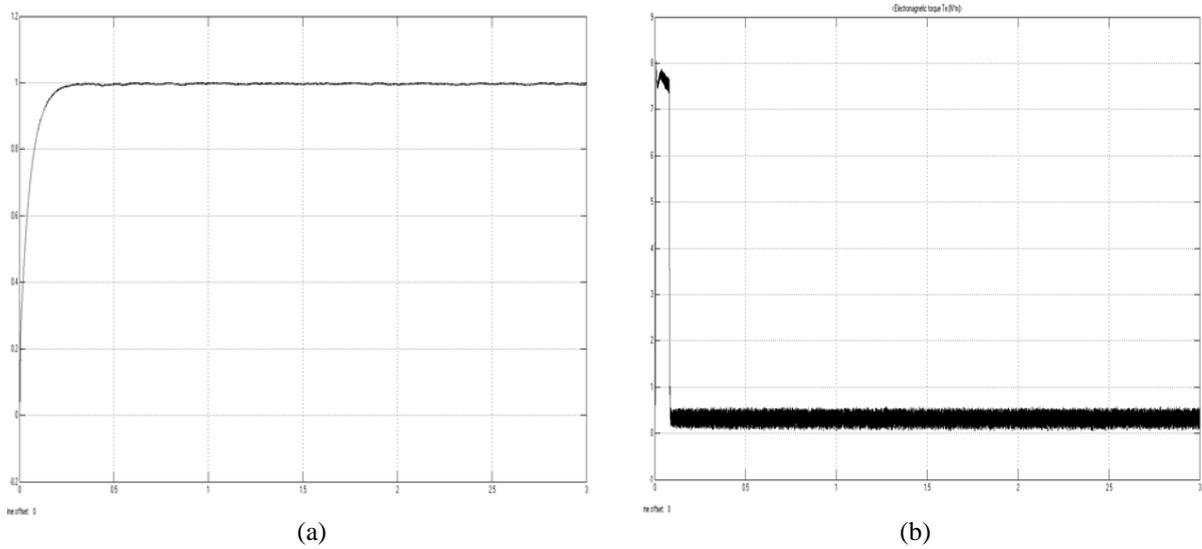


Figure 12 Rotor Flux vs time

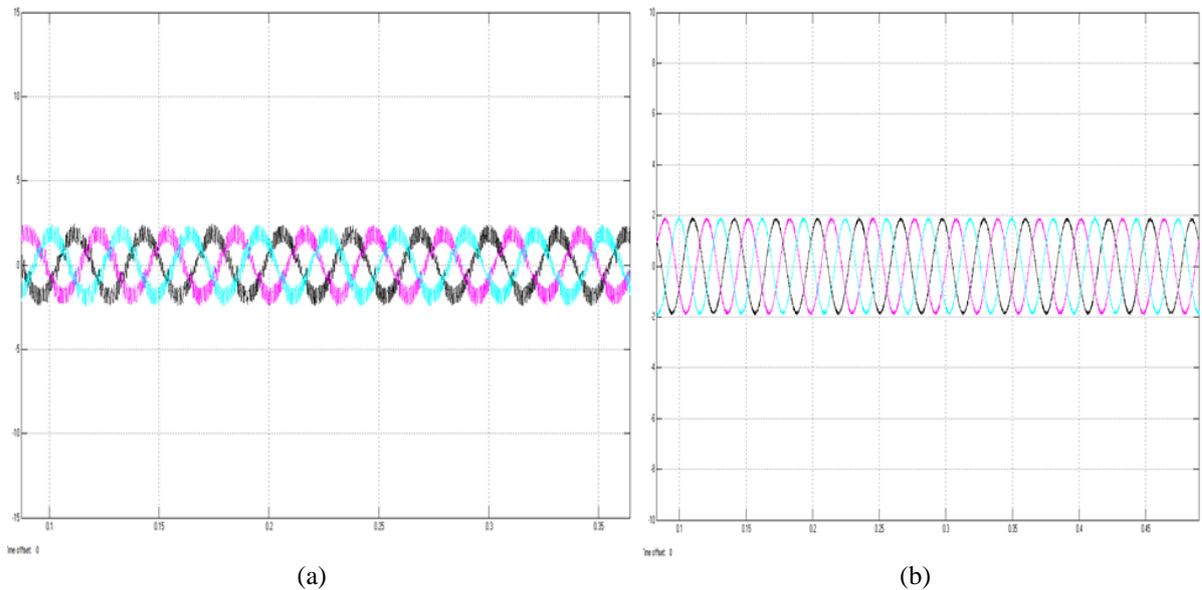


Figure 13 Stator currents Iabc vs time

6. CONCLUSION

Simulink is a graphical extension to MATLAB to develop a model and then perform experiments on it for predicting the behaviour of the systems over time without building it practically. So it is a first step towards designing a system. In this paper detail calculations necessary for the development of the Indirect rotor field oriented control of induction motor drive using Matlab/ Simulink has been presented. The model so developed can be used to study the dynamic behaviour of the induction motor by applying step change in the reference speed and the load torque. From the present model developed, one can implement various types of control schemes by adding subsystems in the present model. This paper will be helpful for the post-graduates and researchers in real time implementation of the drive.

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REFERENCES

- [1] P.Vas. Vector Control of AC Machines, New York: Clarendon 1990
- [2] B.K.Bose, Power Electronics and AC Drives, *Prentice Hall* 1986.
- [3] R.Krishnan, Electric Motor Drives Modelling, Analysis and Control, *Prentice Hall*, 2001.
- [4] Texas Instruments Europe, 'Field Oriented Control of 3-phase AC –Motors,' *Literature NumberBPRA073*, February 1998.
- [5] Xiang Zhao, Huijuan Liu, Jingxiong Zhang, Haijiao Zhang, 'Simulation of Field Oriented Control in Induction Motor Drive System', *Indonesian Journal of Electrical Engineering and Computer Science*, Vol 11 No 12, Dec 2013; 7555-7563
- [6] R Rajendran, Dr. N.Devarajan,'A Comparative Performance Analysis of Torque Control Schemes for Induction Motor Drives', *International Journal of Power Electronics and Drive Systems (IJPEDS)*, Vol.2.No.2,2012;177-191.
- [7] R. Gunabalan, V. Subbiah,'Speed Sensorless Vector Control of Induction Motor Drive with PI and Fuzzy Controller', *International Journal of Power Electronics and Drive Systems (IJPEDS)*,Vol.5.No.3, February 2015; 315-325.
- [8] Bilal Akin and Manish Bharadwaj, 'Sensored Field Oriented control of 3-phase Induction Motors', *Texas Instruments, Application Report SPRABP8*-July 2013.
- [9] Dr.Tilak Thakur, T.Kartik Chandra , C.N.Bhaskar,'Indirect Vector Controlled Induction Motor Propulsion Drive for Marine Applications', *Americal International Journal of Research in Science,Technology, Engineering & Mathematics*, 2(2), March-May2013; 245-249 .
- [10] Pradeep B. Jyoti, J. Amaranath and D.Subbarayudu, ' Evaluation of various types of Indirect Vector Control of Induction Motor Drives', *International Journal of Emerging Technologies in Computational and Applied Sciences (IJETCAS)*, 4(1), March-May 2013;27-36.
- [11] Hamid Khan, 'Field Oriented Control' *Application Note, RENESAS*, 2008

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