

Design of Control System for Feed-forward Current fed Rotor Flux Oriented Induction Machine

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Abstract

Field-oriented control is probably the most common control method used for high-performance induction machine applications. Among the various possible orientations, rotor flux orientation is the most prominent. This paper presents the detail design of control system for current source inverter (2-level voltage) driven rotor flux oriented induction machine. The designed control system is validated by testing on 50HP Induction machine using Matlab/Simulink software. The simulation results shows effectiveness of the designed control system.

Keywords: Induction Machine, Feed-forward Control, Rotor Flux Orientation, 2-level Inverter, Matlab/Simulink

INTRODUCTION

Field Oriented Control can be implemented in feedback or feed forward manner depending on how the reference frame is aligned with the flux vector [1]- [5]. If the alignment is done by the direct measurement of flux estimation then the control is called as Feedback Field Oriented Control. On the other hand if the slip frequency obtained from the rotor dynamic equation is used to achieve field orientation, then the control is called as Feed forward rotor Field Oriented Control.

The main objective of the research presented in this paper is to create a platform for implementing a drive by designing feed forward control system for Field oriented induction motor drive in Matlab environment that helps graduates, post graduates and budding researchers in their future work.

In the subsequent section of the paper, the inverter modulation strategy is presented. Computation of all the values needed for the implementation of the proposed control system, designing of control system, testing of control system and finally the simulation results and conclusions are presented.

INVERTER MODULATION STRATEGY

The output of the inverter fed to an induction motor system is mainly controlled by pulse width modulation (PWM) strategy.

The voltage source inverter (VSI) feeding an induction motor when operated in the current controlled (CC) mode is called as current controlled voltage source inverter (CCVSI). Today, VSI's with CC are employed in every application where fast response, high accuracy, and a high level of performance are needed.

Hysteresis band current control method is one of the several types of PWM techniques. It directly controls the current fed to the motor. It is basically a feedback current control method of PWM where the actual currents are continuously compared with the reference currents within the specified hysteresis band [6]-[10]. It works on the principle that initially when the positive voltage is applied by turning ON the upper switch of the inverter leg, it increases the current. When it hits the upper band, the lower switch is turned ON to keep the actual current within the specified band. Hysteresis controller gives fast transient response. The peak to peak ripple current depends upon the width of the hysteresis band. The ripple in the current can be reduced by reducing the hysteresis band, but this will increase the switching frequency and the switching losses. Hence an optimum hysteresis band is to be selected. The switching frequency in this method does not remain constant but varies along the waveform.

COMPUTATIONS

The Field Oriented Control technique needs more calculations than the other control methods. The computation of all the values needed for the implementation of feed forward rotor field oriented control are : parameters of the motor, the rated rotor flux for rated torque operation, selection of the DC voltage etc. This section describes the calculations required for implementation of feed forward rotor field oriented scheme.

PARAMETER DETERMINATION

Determining the parameters of Induction Machines is very important step while considering Field Oriented Control Technique. The name plate data of the induction motor is mentioned in Table1

Table 1. Name plate Data of Induction Motor

Nominal Power(Pn)	50*746 Watts
Nominal Voltage(Vn)	460 Volts
Nominal Frequency(fn)	60 Hertz
Inertia (J)	1.662 Kg/m ²
Friction Constant(B)	0.1 N-m.sec

Using the traditional methods based on "no-load" and "locked rotor" tests the induction motor equivalent circuit parameters can be identified. The values of them are as tabulated in Table 2

Table 2. Parameters of Induction Motor

Stator Resistance(Rs)	0.087 Ohm
Stator leakage Inductance(Lls)	0.8 mHenry
Rotor Resistance(Rr)	0.228 Ohm
Rotor leakage Inductance (Llr')	0.8 mHenry
Magnetic Inductance(Lm)	34.7 mHenry

COMPUTATION OF RATED FLUX

The q and d-axis voltages in synchronous reference frame are given by-

$$v_{qs} = \frac{V_n * \sqrt{2}}{\sqrt{3}} = \frac{460\sqrt{2}}{\sqrt{3}} = 375.59 \text{Volts} \quad (1)$$

$$v_{ds} = 0 \quad (2)$$

Based on voltage and flux linkages equations, the electrical model of an ideal symmetrical squirrel-cage type induction motor in an arbitrary reference frame can be given in matrix form as follows -

$$[V] = [Z][I]$$

Where

$$[V] = \begin{bmatrix} v_{qs} \\ v_{ds} \\ 0 \\ 0 \end{bmatrix}; [I] = \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix}$$

$$[Z] = \begin{bmatrix} (R_s + L_s p) & \omega_a L_m & L_m p & \omega_a L_m \\ -\omega_a L_m & (R_s + L_s p) & -\omega_a L_m & L_m p \\ L_m p & (\omega_a - \omega_r) L_m & (R_r + L_r p) & (\omega_a - \omega_r) L_r \\ -(\omega_a - \omega_r) L_m & L_m p & -(\omega_a - \omega_r) L_r & (R_r + L_r p) \end{bmatrix} \quad (3)$$

The equation (3) can be used as a general equation for various reference frames by substituting speed of the respective reference frame [11]-[12]. The choice of a reference frame will affect the waveforms of all d-q variables and also the simulation speed as well as the accuracy of the results.

In this paper, an arbitrary reference frame fixed to the rotor rotating at electrical angular velocity of ω_r has been chosen. Hence substituting $\omega_a = \omega_r = 2\pi f_n$ and $p=0$ in the above equation and solving for I_{ds} , I_{qs} , I_{qr} and I_{dr} gives-

$$\begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} = \begin{bmatrix} 0.1824 \\ 28.071 \\ 0 \\ 0 \end{bmatrix} \quad (4)$$

The flux linkages are given by-

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \quad (5)$$

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \quad (6)$$

$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs} \quad (7)$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds} \quad (8)$$

From these calculated values of currents and using equations (7) and (8), the rotor flux linkages are determined as-

$$\lambda_{qr} = 0.0063 \text{ Wb}$$

$$\lambda_{dr} = 0.9738 \text{ Wb}$$

Substituting the corresponding values, the resultant rotor (rated) flux is determined by-

$$\lambda_r = \sqrt{\lambda_{qr}^2 + \lambda_{dr}^2} = \lambda_r^* = 0.9738 \text{Wb} \quad (9)$$

The electromagnetic torque developed by the motor is given by

$$T_{em} = \left(\frac{3}{2}\right) \left(\frac{P}{2}\right) (\lambda_{qr} i_{dr} - \lambda_{dr} i_{qr}) \quad (10)$$

The mechanical equation is given by-

$$J \frac{d\omega_m}{dt} = T_{em} - T_{load} - K_d \omega_m \quad (11)$$

SELECTION OF DC LINK VOLTAGE (VDC)

Induction motor is fed by a current-controlled PWM inverter which has 2- voltage levels. For a 2-level inverter, line-to-line voltage is:

$$V_{L-L} = 0.612 * m_{index} * V_{dc} \quad (12)$$

Since modulation index ≤ 1 , DC link voltage is:

$$V_{DC} \geq \frac{V_{L-L}}{0.612} \geq \frac{460}{0.612} \geq 752 \text{ So } V_{DC} \text{ is chosen as } 780 \text{ Volts.}$$

COMPUTATION OF RATED AND MAXIMUM TORQUE LIMIT

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

$$T_L = T_e = T_{sh} = P_n / \omega_s \approx 200 \text{ N-m.} \quad (13)$$

$$\text{Maximum torque limit} = 1.5 * \text{Rated torque} = 300 \text{ N-m.} \quad (14)$$

SELECTION OF SAMPLING TIME

The sampling time should not be larger than one-tenth of the smallest time constant in the model. For example, for a 1 kHz switching frequency, the switching period is 1 ms; then, a sampling time of 0.1 ms would do the job. Selecting a smaller sampling time than required, will increase the simulation time. Thus for 10 KHz switching frequency, the sampling time is –

$$T_s = \frac{1/f_{sw}}{10} = \frac{1/10000}{10} = 0.01 \text{ msec} \quad (15)$$

SELECTION OF HYSTERESIS BAND LIMIT

For hysteresis current controller, the optimum band limit selected is $\pm 0.5A$

DESIGN OF CONTROL SYSTEM

FLUX PI CONTROLLER

Proportional gain and the integral gain, K_{pf} & K_{if} , are the parameters of flux PI controller. The block diagram shown in figure 1 is used to design the flux controller.

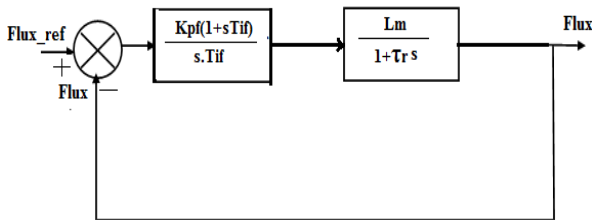


Figure 1. Block diagram of Flux controller

The open-loop transfer function is given as-

$$G_c(s)G(s) = \frac{LmK_{pf}(1+sT_{if})}{sT_{if}(1+\tau s)} \quad (16)$$

Using Internal Model Control (IMC), the parameters are designed as follows-

$$G_c\phi(s) = \frac{\tau}{LmT_\phi} + \frac{1}{LmT_\phi s} \quad (17)$$

Where T_Φ is Time constant of flux closed loop transfer function

Since $\tau \gg T_i$, choosing $T_\Phi = 10 \text{ msec}$

$$G_c\phi(s) = 449.57 + \frac{2881.844}{s}$$

Hence for flux PI controller, the parameters are $K_{pf} = 449.57$ and $K_{if} = 2881.844$

SPEED PI CONTROLLER

Proportional gain and the integral gain, K_{ps} & K_{is} , are the parameters of speed PI controller. The block diagram shown in figure 2 is used to design the speed controller.

$$K_t = (3/2)(P/2)\lambda_{dr} = 2.8556;$$

$$K_m = K_t/K_d = 5.7112;$$

$$\tau_m = J/K_d = 3.3240$$

The open loop transfer function is given as-

$$G_c(s)G(s) = \frac{K_m K_p (1+sT_i)}{sT_i(1+\tau_m s)} \quad (18)$$

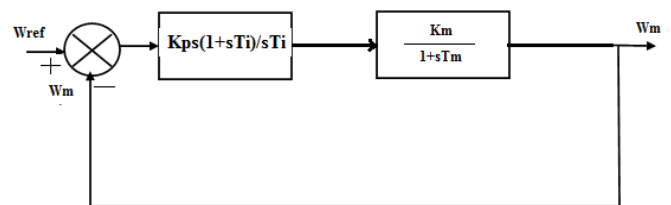


Figure 2. Block diagram of Speed Control loop

Hence the closed loop transfer function is given as-

$$T(s) = \frac{K_m K_p s (1+sT_i)}{sT_i(1+\tau_m s) + K_m K_p s (1+sT_i)} \quad (19)$$

After simplifying, we get-

$$T(s) = \frac{\left(\frac{K_m K_p s}{\tau_m T_i}\right)(1+sT_i)}{s^2 + \left(\frac{K_m K_p s + 1/\tau_m}{\tau_m}\right)s + \left(\frac{K_m K_p s}{\tau_m T_i}\right)} \quad (20)$$

Using pole placement method, poles are placed at $s = -p_1$ and $s = -p_2$ and assumed that p_1 is dominant pole.

Choosing $p_1 = 5$ and $p_2 = 10 * p_1 = 50$

$$\tau_m(p_1 + p_2) - 1/K_m = K_{ps} = 31.8358$$

$$T_i = \frac{(K_m K_{ps})}{\tau_m p_1 p_2}$$

Hence $K_{is} = K_{ps}/T_i = 145.5042$

TESTING OF CONTROL SYSTEM

Figure 3 shows the block diagram of the Feed forward Rotor Field Oriented control system. The designed control system is now validated by testing on Matlab/ Simulink for the Feed forward Rotor Field Oriented control algorithm.

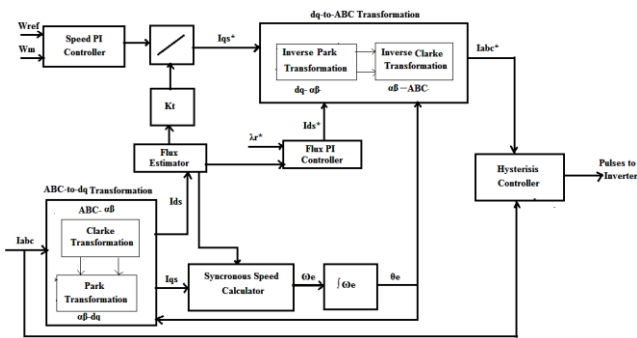


Figure 3. Block diagram of Feed forward Rotor Field Oriented control algorithm

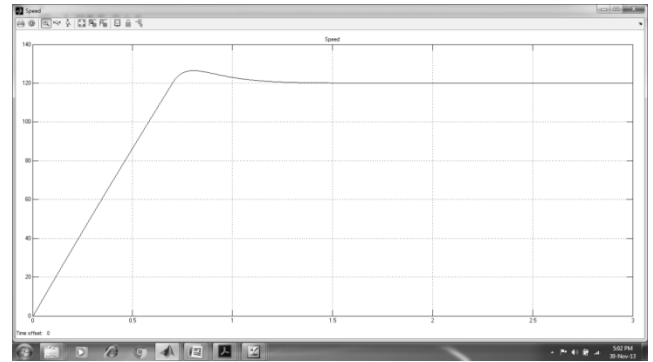


Figure 5. Speed vs time

The complete simulink model for feed forward rotor field oriented control algorithm using Matlab is shown in figure 4 which is now ready for simulation[13]-[18].

Before starting the simulation, a .m file is prepared consisting of name plate data and the parameters of the motor along with all design formulae presented in the above sections and is executed at the Matlab prompt so that all the values of the variables in the Simulink model will be assigned to them.

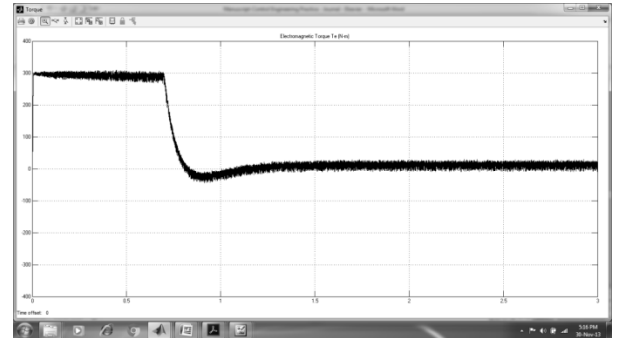


Figure 6. Electromagnetic Torque vs Time

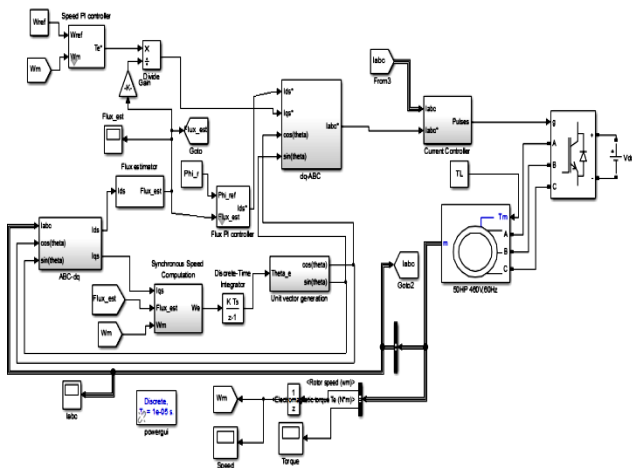


Figure 4. Feed forward Rotor Field Oriented control algorithm using Matlab/Simulink

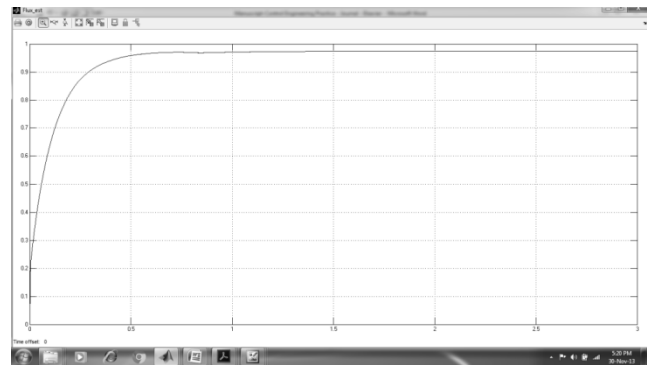


Figure 7. Estimated flux vs Time

SIMULATION RESULT

SCENARIO 1

Initially the reference speed is set to a constant value of 120 rad/s and the load torque is kept constant at 0 N-m. The simulation is run for 3 sec and the responses are observed on the respective scopes. The response curves for Rotor speed, Electromagnetic Torque T_e^* , Estimated flux and stator currents I_{abc} vs time are observed and are shown in figure 5-figure 8.

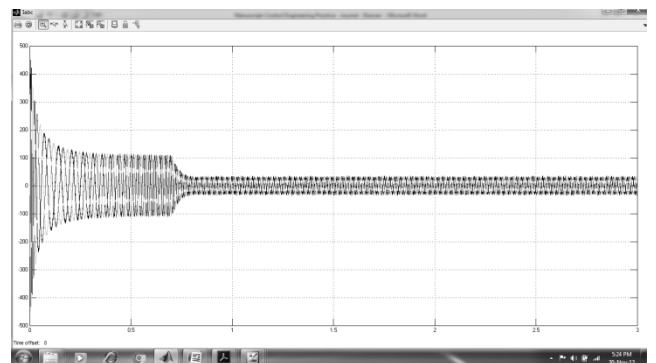


Figure 8. Stator currents, I_{abc} vs Time

SCENARIO 2

At $t=0$ sec, the reference speed is set to 120 rad/sec and reversed to -120 rad/sec at $t=1.6$ sec. The simulation is run for 5 sec and the responses are observed on the respective scopes. The response curves for Rotor speed, Electromagnetic Torque T_e^* , Estimated flux and stator currents i_{abc} vs time are observed and are shown in figure 9- figure 12.

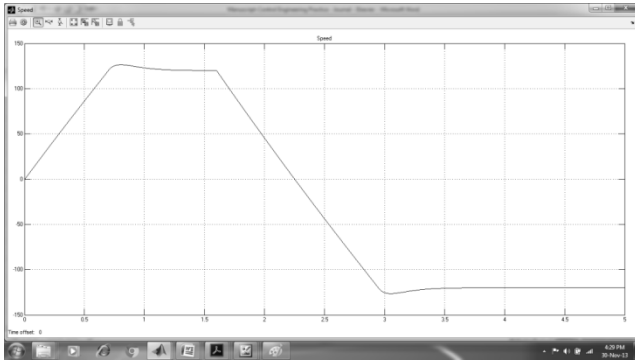


Figure 9: Speed vs time

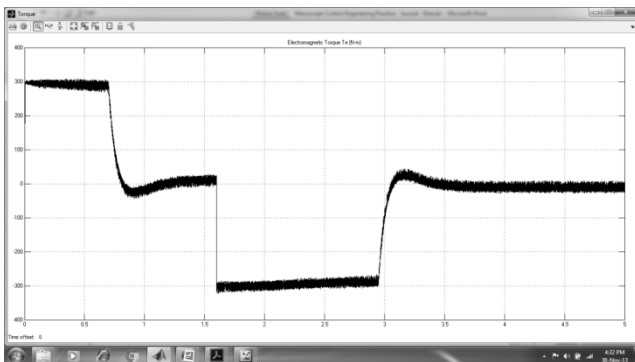


Figure 10. Electromagnetic torque T_e^* vs time

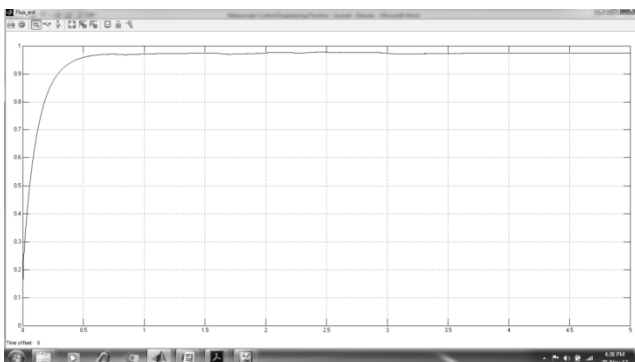


Figure 11. Estimated flux vs time

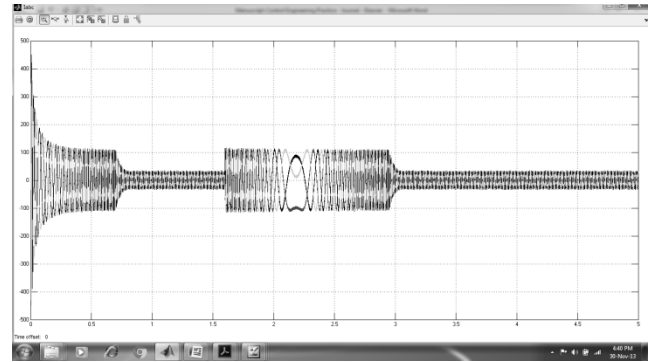


Figure 12. Stator currents i_{abc} vs time

CONCLUSION

This paper explains the theoretical aspects used in simulation and implementation of feed forward rotor field oriented control for current controlled voltage source inverter fed induction motor drive incorporating conventional PI controller. The proposed control strategy is successfully implemented using Matlab/Simulink on 50 HP induction motor. The simulation results presented in this paper shows that the stator currents, motor speed and torque follow the references closely.

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