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Indirect Vector Control of Induction Motor Drive Using Nonlinear Controller

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***Abstract*— This paper presents an implementation of nonlinear controller in speed regulation of induction motor drive using indirect vector control method. The proposed nonlinear controller is designed using passivity based control technique and Hamiltonian structure of inverter fed induction motor. The nonlinear controller is used to improve the stability and reduce the losses of the induction motor drive. The proposed method has been simulated using MATLAB/Simulink software.**

***Keywords:* Induction motor, nonlinear control, passivity based control, stability, minimum losses.**

I. INTRODUCTION

The three phase Induction Motor(IM) is mostly used in an industries for variable speed applications because of its robustness and less maintenance. There are various control strategies for controlling the inverter-fed induction motor for good steady state but poor dynamic response[1]. An air gap flux linkages is the cause for poor dynamic response thus the variations in the flux linkages have to be controlled by the magnitude and frequency of the stator and rotor phase currents. This control is achieved by vector control because it relates to the phasor control of the rotor flux linkages. Vector control made the ac drives equivalent to dc drives in the independent control of flux and torque to make the dynamic performance better[2].

The design of speed controller is based on the Hamiltonian structure of inverter fed induction motor and passivity control method. Passive systems are a class of dynamical systems in which the energy exchange. In passive systems the rate at which the energy flows into the system is not less than the increase in storage[3]. Passivity Based Control (PBC) [4] method is used to design the controller based on the dynamics of the machine was decomposed as the feedback interconnection of two passive subsystems-electrical and mechanical and nonlinear damping was injected to make the electrical subsystem strictly passive [5]. The energy shaping controller is considered to generate the desired torque[6].PBC does not require the knowledge of rotor flux but Input-Output Linearization, Back stepping [7],Feedback linearization and sliding mode control requires the knowledge of rotor flux [8]. Theglobal stability of the induction motor position control system is formally proved by the passivity theory.

The paper is organized as follows. In section II, describes the dynamic model of induction motor. In section III, the principle of indirect vector control of induction motor is explained. In section IV, the proposed nonlinear controller design is presented. Simulation and its results are explained in sections V and VI. Finally in section VII, some conclusions are drawn.

II. DYNAMIC MODEL OF INDUCTION MOTOR

The stator of induction motor consists of three phase balanced distributed windings with each phase separated from other two windings by 120 degrees in space .When current flows through these windings, three phase rotating magnetic field is produced. The dynamic behavior of the induction machine is taken into account in an adjustable speed drive system using a power electronics converter. This machine constitutes an element within a feedback loop. Study of the dynamic performance of the machine is complex due to coupling effect of the stator and rotor windings, also the coupling coefficient varies with rotor position. So a set of differential equations with time varying coefficients describe the machine model [1].

To derive the dynamic model of the machine, the following assumptions are made:

- No magnetic saturation
- No saliency effects i.e. machine inductance is independent of rotor position
- Stator windings are so arranged as to produce sinusoidal mmf distributions
- Effects of the stator slots may be neglected
- No fringing of the magnetic circuit
- Constant magnetic field intensity, radially directed across the air-gap
- Negligible eddy current and hysteresis effects

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A balanced three phase supply is given to the motor from the power converter. For dynamic modeling of the motor two axes theory is used. According to this theory the time varying parameters can be expressed in mutually perpendicular direct (d) and quadrature (q) axis. For the representation of the d-qdynamic model of the machine a stationary or rotating reference frame is assumed.

In stationary reference frame the $d_s$and$q_s$axes are fixed on the stator, whereas these are rotating at an angle with respect to the rotor in rotating reference frame. The rotating reference frame may either be fixed on the rotor or it may be rotating at synchronous speed. In synchronously rotating reference frame with sinusoidal supply the machine variables appear as dc quantities in steady state condition.

Machine model in stationary frame by Stanley equations substituting $\omega_e = 0$. The stator circuit equations are written as:

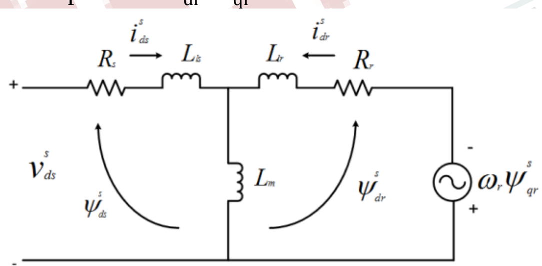
$$v_{qs}^{s} = R_s i_{qs}^{s} + \frac{d}{dt}\Psi_{qs}^{s} \quad (1)$$

$$v_{ds}^{s} = R_s i_{ds}^{s} + \frac{d}{dt}\Psi_{ds}^{s} \quad (2)$$

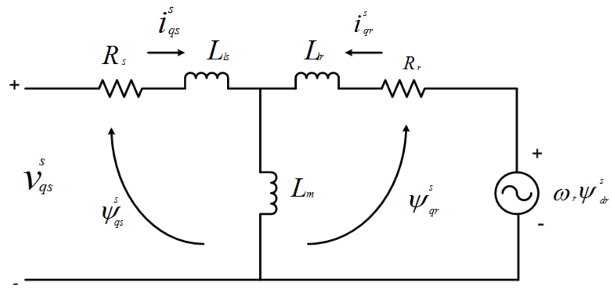
$$0 = R_r i_{qr}^{s} + \frac{d}{dt}\Psi_{qr}^{s} - \omega_r \Psi_{dr}^{s} \quad (3)$$

$$0 = R_r i_{dr}^{s} + \frac{d}{dt}\Psi_{dr}^{s} + \omega_r \Psi_{qr}^{s} \quad (4)$$

Where $\Psi_{qs}^{s}, \Psi_{ds}^{s}$ – q-axis and d-axis stator flux linkages
$\Psi_{qr}^{s}, \Psi_{dr}^{s}$ –q-axis and d-axis rotor flux linkages
R_s, R_r –stator and rotor resistances
ω_r –rotor speed and $v_{dr} = v_{qr} = 0$



(a)



(b)

Fig. 1. d^s-q^s equivalent circuits

The electromagnetic torque is developed by the interaction of air gap flux and rotor mmf which can be expressed in general vector form as

$$T_e = \frac{3}{2}\frac{P}{2}(\overline{\Psi_m}) * (\overline{I_r}) \quad (5)$$

The torque equations can be written in stationary frame with corresponding variables as

$$T_e = \frac{3}{2}\frac{P}{2}(\Psi_{dr}^{s} i_{qr}^{s} - \Psi_{qr}^{s} i_{dr}^{s}) \quad (6)$$

III. VECTOR CONTROL OF INDUCTION MOTOR

Field Orientation Control or vector control of induction machine achieves decoupled torque and flux dynamics leading to independent control of torque and flux as for a separately excited DC motor. This is achieved by orthogonal projection of the statorcurrent into a torque-producing component and flux-producing component. This technique is performed by two basic methods: direct and indirect vector control. With direct filed orientation, the instantaneous value of the flux is required and obtained by direct measurement using flux sensors of flux estimators, whereas indirect field orientation is based on the inverse flux model dynamics and there are three possible implementation based on the stator, rotor or air gap flux orientation. The rotor flux indirect vector control technique is the most widely used due to its simplicity.

Principle Of Indirect Vector Control

In direct vector control the field angle is calculated by using terminal voltages and current or Hall sensors or flux sense windings. The principal vector control parameters, i_{ds}^{*} and i_{qs}^{*}, which are dc values in the synchronously rotating reference frame, are converted to the stationary reference frame (using the Vector Rotation (VR) block) by using the unit vector $\cos\theta_e$ and $\sin\theta_e$. These stationary reference frame control parameters i_{ds}^{s*} and i_{qs}^{s*} are then changed to the phase current command signals, i_a^{*}, i_b^{*}, and i_c^{*} which are fed to the PWM inverter. A flux control loop is used to precisely control the flux. Torque control is achieved through the current i_{qs}^{*} which is

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generated from the speed control loop.The torque can be negative which will result in a negative phase orientation for i_{qs} in the phasor diagram which is shown in fig. 2. [9]

The rotor circuit equations can be written as

$$\frac{d\Psi_{dr}}{dt} + R_r i_{dr} - (\omega_e - \omega_r)\Psi_{qr} = 0 \quad (7)$$

$$\frac{d\Psi_{qr}}{dt} + R_r i_{qr} - (\omega_e - \omega_r)\Psi_{dr} = 0 \quad (8)$$

The rotor flux linkage expressions can be given as

$$\Psi_{dr} = L_r i_{dr} + L_m i_{ds} \quad (9)$$

$$\Psi_{qr} = L_r i_{qr} + L_m i_{qs} \quad (10)$$

From the above equations we can write

$$i_{dr} = \frac{1}{L_r}\Psi_{dr} - \frac{L_m}{L_r} i_{ds} \quad (11)$$

$$i_{qr} = \frac{1}{L_r}\Psi_{qr} - \frac{L_m}{L_r} i_{qs} \quad (12)$$

The rotor currents in equations (7) and (8), which are inaccessible, can be eliminated with the help of equations (11) and (12) as

$$\frac{d\Psi_{dr}}{dt} + \frac{R_r}{L_r}\Psi_{dr} - \frac{L_m}{L_r} R_r i_{ds} - \omega_{sl}\Psi_{qr} = 0 \quad (13)$$

$$\frac{d\Psi_{qr}}{dt} + \frac{R_r}{L_r}\Psi_{qr} - \frac{L_m}{L_r} R_r i_{qs} - \omega_{sl}\Psi_{dr} = 0 \quad (14)$$

Where $\omega_{sl} = \omega_e - \omega_r$

For decoupling control [1], it is desirable that

$$\Psi_{qr} = 0 \quad (15)$$

That is,

$$\frac{d\Psi_{qr}}{dt} = 0 \quad (16)$$

So that the total flux $\widehat{\Psi}_r$ is directed on the d^e axis.

Substituting the above equations (13) and (14) we get

$$\frac{L_r}{R_r}\frac{d\widehat{\Psi}_r}{dt} + \widehat{\Psi}_r = L_m i_{ds} \quad (17)$$

$$\omega_{sl} = \frac{L_m R_r}{\widehat{\Psi}_r L_r} i_{qs} \quad (18)$$

Where $\widehat{\Psi}_r = \Psi_{dr}$

If rotor flux $\widehat{\Psi}_r$ = constant, then

$$\widehat{\Psi}_r = L_m i_{ds} \quad (19)$$

In other words, the rotor flux is directly proportional to current i_{ds} in steady state.

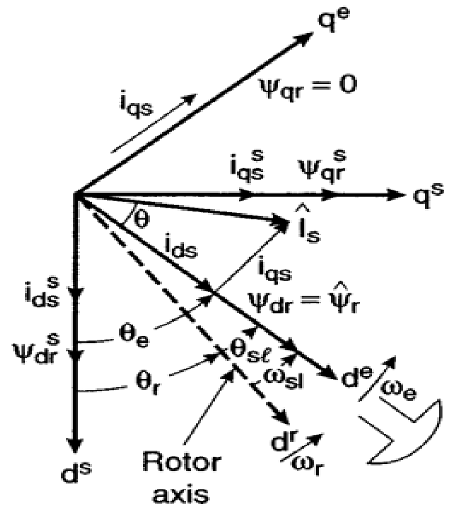

Fig. 2. Phasor diagram of indirect vector control of induction motor

IV. PROPOSED NONLINEAR CONTROLLER DESIGN

To minimize power losses, the flux norm reference should be proportional to the square root of the desired torque, at least as long as the resulting reference is below the maximum allowable value [10] [11].

$$P_{loss} = P_{supplied} - P_{mech}$$

$$= \frac{3}{2}(V_{ds} i_{ds} + V_{qs} i_{qs}) - T_e \omega_r$$

P_{loss} minimization requires an optimal rotor flux λ_r^{opt} [13],

$$(\lambda_r^{opt})^2 = \sqrt{\left(\frac{L_r^2}{p^2} + \frac{R_r L_m^2}{R_s p^2}\right)} \, |T_d|$$

The proposed nonlinear controller is used for speed control of induction motor and minimize the power losses [12]. The method of nonlinear controller is as follows:

Considering the non-linear and multi-variable induction motor model assumptions,

a) Ignore magnetic circuit saturation, the self-inductance and mutual inductance of each winding are constant.
b) Ignore iron losses.
c) Ignore the resistance changing caused by frequency and temperature changing.

Based on the d-qsynchronous rotating reference frame (the energy properties of the system are invariant under a

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change of coordinates), the state equation of induction motor is taken.

Then considering the Euler Lagrange model of induction motor the following equation is derived as [13]

$M\dot{x}$=(J(x, m_{ds} , m_{qs})-R)x+G€

And the desired energy function is W= $\frac{1}{2}x^T$Mx[14].

The whole system can be decomposed into the feedback interconnection of two passive subsystems. The decomposition of induction motor is the design of PBC only for the electrical subsystem using as storage function of the electrical total energy.

An electrical subsystem $\sum_e$ depicts the mapping of $\begin{bmatrix} u \\ -\omega \end{bmatrix}$ onto $\begin{bmatrix} i \\ y \end{bmatrix}$, and a mechanical subsystem $\sum_m$ depicts the mapping of [y(i,θ) − y_L] onto ω .

$\sum_e : \begin{bmatrix} u \\ -\omega \end{bmatrix} \mid \longrightarrow \begin{bmatrix} i \\ y \end{bmatrix}$

$\sum_m$: [y(i,θ) − y_L] | $\xrightarrow{\omega}$

Determine the torque using vector control of induction motor. Then inject constant damping matrix k where k=[k_1 k_2 0].

The torque control system of induction motor based on passivity track time-varying torque only require to build speed error feedback, the desired torque can be given by a PI controller, describe as below [15]

$z^* = k_p(i_{ds} - \frac{i_{qs}}{i_{opt}}) - k_i \int (\omega_r - \omega_r^{ref})\, dt$

Where k_p and k_i denote proportional and integral gain.

Thus the speed of the motor is controlled using passivity based control.

V.SIMULINK MODEL OF INDIRECT VECTOR CONTROL OF INDUCTION MOTOR DRIVE WITH NONLINEAR CONTROLLER

A simulink model of voltage source inverter fed induction motor drive is shown in fig. 3. The synchronously rotating d-q reference frame is considered for both induction motor and voltage source inverter. Considering the dynamic model of the system a simple nonlinear controller is proposed. An indirect vector controlat steady state is used to achieve the speed regulation and losses minimization. The complete system is nonlinear. In order to improve the stability and convergence to the desired equilibrium of the motor, the nonlinear controller is used. The error value of stator current and speed is given to the nonlinear controller and the output signal is given to the PWM module.The signal from the PWM module isgiven totheinverter and further the speed of the motor gets regulated. The speed regulation and losses minimization is obtained from simulink model of indirect vector control of induction motor drive.

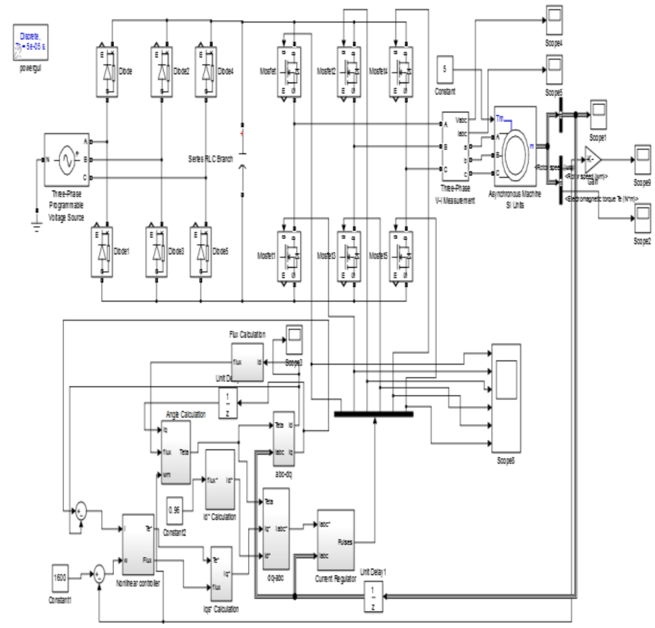

Fig. 3. Simulink model of indirect vector control of induction motor drive with nonlinear controller

VI. SIMULATION RESULTS

The reference speed is set as 1600 rpm. The speed of the motor is settled at 1650 rpm. The settling time is 2.4s. The regulated speed is shown in fig. 4.

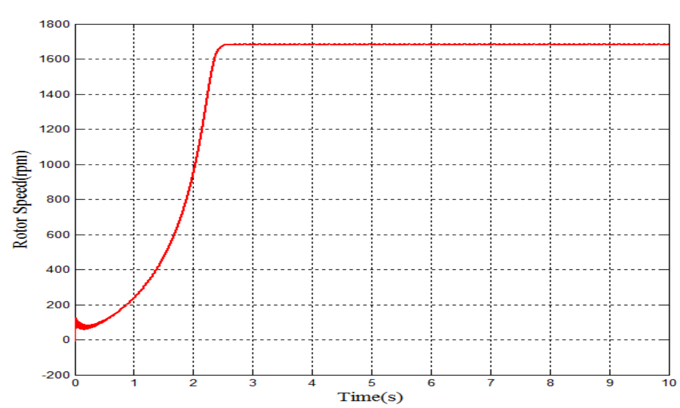

Fig. 4. Rotor speed characteristic of induction motor

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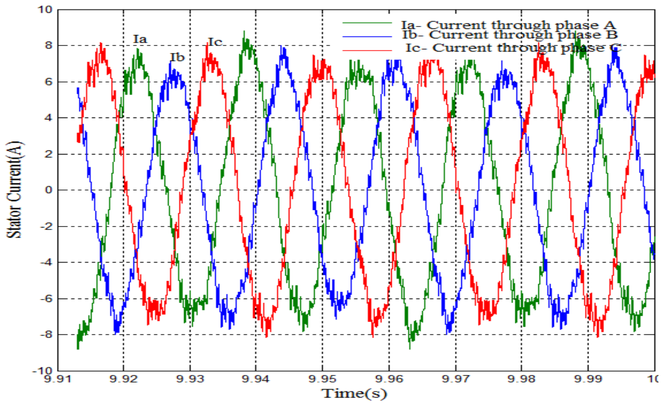

Fig. 5. Stator current characteristics of induction motor

Fig.5.shows the stator current of induction motor. It is observed that the stator current of the motor is 8A. The settling time is 9s.

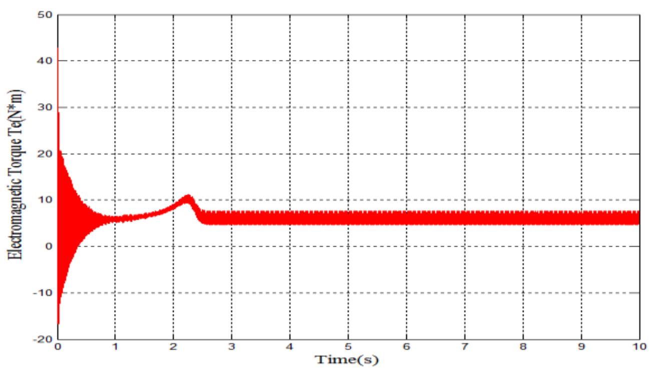

Fig. 6. Electromagnetic torque characteristics of induction motor

Fig. 6. Shows the electromagnetic torque of the induction motor. It is observed that the torque of the motor is 5 Nm. Settling time is 2.3s.

VII. CONCLUSION

Thus the speed control of Field Oriented Control (FOC) of induction motor with minimum losses is achieved using the nonlinear controller. The proposed system is simulated using MATLAB simulink and the simulation results show that the complete nonlinear closed-loop system stability converges to the desired equilibrium and remains bounded.

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