Modeling and Simulation of Self-Tuning PI Control for Electrical Machines

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Abstract – This paper presents the work of modeling and simulation of a self-tuning PI control for induction motors. A mathematical model of a three-phase induction motor, together with its self-tuning PI controller will be illustrated. By using the computer simulation, it has been found that the proposed design approach is robust to the variations of induction motor parameters and it achieves the performance of global asymptotic speed tracking.

Keywords - Modeling and simulation, self-tuning PI control, indirect vector control, induction motor

I. INTRODUCTION

The conventional proportional-integral (PI) control remains the most popular design approach used in industrial applications due to its simplicity and reliability for the control of first and second order plants, and even high order plants with well-defined conditions. A well-tuned PI controller is capable in achieving an excellent performance. However, it suffers a crucial disadvantage of getting a poor performance whenever the plant is subjected to some kind of disturbance or, the plant has high order nonlinear structure. Induction motor is a prime choice of variable-speed drive in a wide range of applications due to its low cost, reliability, and ruggedness. Because of the highly coupled non-linearity and the variations of internal parameters, the tuning of PI controller becomes a challenging problem when the conventional PI design is applied to the control problem of induction motors [1], [2]. In order to deal with this problem, self-tuning PI control for induction motor drive has received considerable attention in the literature [3], [4], and [5]. In this paper, we have adopted a self-tuning PI control which has been developed in [6]. Consequently, the PI control gains in this design are automatically adjusted online. Therefore, this makes our controller being robust to the changes of induction motor parameters.

Modeling and simulation is usually used in designing a motor drive in order to avoid building a system prototype due to the high expense. If all components are correctly selected, the simulation process could demonstrate both the steady state and the dynamic performance that would have been obtained if the drive was actually needed. This practice saves time, and reduces the cost of building a prototype, and most importantly it ensures that the requirements are being achieved.

Furthermore, simulation-based design plays an important role in understanding and evaluating induction motor drives. Recently, the work of modeling and simulation by using Matlab / Simulink has been widely used in the Along this way, we developed an entire simulation program for the whole system and also created several unique modules to replace the existing ones in Matlab/Simulink. For example, in order to visualize clearly the relationship between internal parameters and system performances, all of the differential equations have been embedded into the models of electrical machines. The theoretical derivation, modeling work, and simulation results will be illustrated as follows.

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II. THE PRINCIPLE OF INDUCTION MOTOR MODELING WITH INDIRECT VECTOR CURRENT CONTROL

Given several assumptions ([7] and [8]), the dynamical model of an induction motor in a fixed reference frame attached to the stator can be described as follows:

$$\frac{d\omega}{dt} = \frac{M}{JL_r}(\psi_a i_b - \psi_b i_a) - \frac{T_L}{J} \tag{1}$$

$$\frac{d\psi_a}{dt} = -\frac{R_r}{L_r}\psi_a - \omega\psi_b + \frac{R_r}{L_r}Mi_a \tag{2}$$

$$\frac{d\psi_b}{dt} = -\frac{R_r}{L_r}\psi_b + \omega\psi_a + \frac{R_r}{L_r}Mi_b \tag{3}$$

$$\frac{di_a}{dt} = \frac{MR_r}{(L_rL_s - M^2)L_r}\psi_a + \frac{M}{L_rL_s - M^2}\omega\psi_b \tag{4}$$

$$\frac{di_b}{dt} = \frac{MR_r}{(L_rL_s - M^2)L_r}\psi_b - \frac{M}{L_rL_s - M^2}\omega\psi_a - \frac{M^2R_r + L_r^2R_s}{(L_rL_s - M^2)L_r}i_b + \frac{L_r}{L_rL_s - M^2}u_b \tag{5}$$

where: rotor speed ω, rotor fluxes (ψ_a, ψ_b), and stator currents (i_a, i_b) are state variables. rotor inertia J, stator and rotor inductances (L_s, L_r), mutual inductance M, stator and rotor resistances (R_s, R_r) are system parameters. Control inputs are stator voltages (u_a, u_b).

For the purpose of current control of induction motor using the technique of rotor-flux-oriented vector control, the model of induction motor can be represented on d-q rotating axis, where the d-axis is aligned with the rotor flux at all time and the q-axis is always 90° ahead of the d-axis. Therefore, we take new variables similar to [9] and [10] as follows.

$$\begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} = \begin{bmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{bmatrix} \begin{bmatrix} \psi_a \\ \psi_b \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} cos\varphi & sin\varphi \\ -sin\varphi & cos\varphi \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} cos\varphi & sin\varphi \\ -sin\varphi & cos\varphi \end{bmatrix} \begin{bmatrix} u_a \\ u_b \end{bmatrix} \quad (8)$$

variables on left side represent the components of rotor fluxes, stator currents and stator voltage vectors, respectively, with respect to the d-q rotating axis at speed ω_e and identified by the angle φ. In the new state variables $(\omega, \psi_d, \psi_q, i_d, i_q)$ and new control inputs (u_d, u_q), the motor dynamics become:

$$\frac{d\omega}{dt} = \frac{M}{JL_r}(\psi_d i_q - \psi_q i_d) - \frac{T_L}{J} \quad (9)$$

$$\frac{d\psi_d}{dt} = \frac{R_r M}{L_r} i_d - \frac{R_r}{L_r}\psi_d + (\omega_e - \omega)\psi_q \quad (10)$$

$$\frac{d\psi_q}{dt} = \frac{R_r M}{L_r} i_q - \frac{R_r}{L_r}\psi_q - (\omega_e - \omega)\psi_d \quad (11)$$

$$\frac{di_d}{dt} = -\left(\frac{L_r R_s}{L_r L_s - M^2} + \frac{M^2 R_r}{(L_r L_s - M^2)L_r}\right) i_d + \omega_e i_q + \frac{MR_r}{(L_r L_s - M^2)L_r}\psi_d + \frac{M}{L_r L_s - M^2}\omega\psi_q + \frac{L_r}{L_r L_s - M^2}u_d \quad (12)$$

$$\frac{di_q}{dt} = -\left(\frac{L_r R_s}{L_r L_s - M^2} + \frac{M^2 R_r}{(L_r L_s - M^2)L_r}\right) i_q - \omega_e i_d + \frac{MR_r}{(L_r L_s - M^2)L_r}\psi_q + \frac{M}{L_r L_s - M^2}\omega\psi_d + \frac{L_r}{L_r L_s - M^2}u_q \quad (13)$$

when the current-controlled PWM inverter is applied, the model can be reduced to a third-order system, which is widely used in the induction motor control design ([11], [12], and [13]).

$$\frac{d\omega}{dt} = \frac{M}{JL_r}(\psi_d i_q - \psi_q i_d) - \frac{T_L}{J} \quad (14)$$

$$\frac{d\psi_d}{dt} = \frac{R_r M}{L_r} i_d - \frac{R_r}{L_r}\psi_d + (\omega_e - \omega)\psi_q \quad (15)$$

$$\frac{d\psi_q}{dt} = \frac{R_r M}{L_r} i_q - \frac{R_r}{L_r}\psi_q - (\omega_e - \omega)\psi_d \quad (16)$$

According to the rotor-flux-oriented vector control ([14] and [15]), the rotor flux is aligned with the *d* axis and kept at a constant so that we have the following relations in steady state:

$$\psi_q = \dot{\psi}_q = 0 \quad (17)$$

$$\psi_d = \psi_r = const. \quad (18)$$

Applying (17) and (18) into (15) and (16), we can get the slip frequency and the flux current in steady state

$$\omega_s = \omega_e - \omega = \frac{R_r M}{L_r \psi^*} i_q = \frac{M}{T_r \psi^*} i_q \quad (19)$$

$$i_d = \frac{\psi^*}{M} \quad (20)$$

The vector control technique shown above guarantees that the transient terms vanish in short time. Therefore, the steady state equations are sufficient for the derivation of speed control design. The control objective now is to design a speed controller so that ω tracks ω^*. As a consequence, Fig. 1, in which $K_T = \frac{M\psi^*}{L_r}$, shows the block diagram of speed control design.

III. SELF-TUNING PI CONTROL DESIGN

Due to its simplicity and reliability, the conventional PI control remains the most popular method used in motor control. However, since the variation and the high uncertainty of induction motor internal parameters, the tuning of PI control gains becomes a challenging problem. In this study, we apply the concept that has been presented in [6] to develop a self-tuning PI control and eliminate any dependence on the control model of induction motor. First, we divide the whole system into three parts as shown in Fig. 2, which is similar to the one given in [16]. Part 1 is the proportional part with the exception of proportional gain K_P. Part 2 is the integral part with the exception of integral gain K_I. Part 3 is the control plant. Then we consider K_P and K_I as independent variables. Based on the principle of gradient descent optimization, we construct a cost function as

$$E = \frac{1}{2}e^2 = \frac{1}{2}(\omega^* - \omega)^2 \quad (21)$$

Using the algorithm of gradient descent

$$\dot{K} = -\eta \frac{dE}{dK}, \; K = \{K_P, K_I\} \quad (22)$$

and following the derivative of chain rule, we can obtain the following tuning algorithm

$$\dot{K}_P = \eta e y_1 \\ \dot{K}_I = \eta e y_2 \quad (23)$$

where η is an adaptive coefficient.

IV. SIMULATION RESULTS

In order to evaluate and validate the effectiveness of our proposed control design presented in the previous sections, a simulation program has been developed by using Matlab/ Simulink. Fig. 3 shows the block diagram of the entire motor drive system. The module of the simulation program is shown in Fig. 4. Fig. 5 shows the model of induction motor. The specifications for the induction motor are [17]: motor power = 15*kW* (rated), load torque = 70*Nm* (rated), rotor flux linkage = 1.3*Wb* (rated), angular speed = 220 *rad/s* (rated), n = 1, J = 0.0586kgm^2, R_S = 0.18Ω, L_S = 0.0699H, M = 0.068H, R_r = 0.15Ω, Lr = 0.0699H. In our simulation, we take the change of rotor resistance as $R_S(t) = R_S*(2 - exp(-at))$ in which a = 2 and give different load torques.

Let us see the dynamic behaviors of induction motor from the results of Fig. 6 when the motor runs in four quadrants. Fig. 6(a) shows that the motor runs without load. Fig. 6(b) presents that the motor runs with 100% load. In Fig. 6, one can see that the control system of induction motor achieves a good tracking performance.

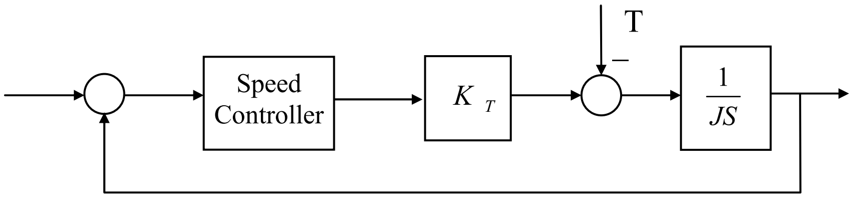


Fig. 1: Speed control design for induction motor with rotor-flux-oriented vector control

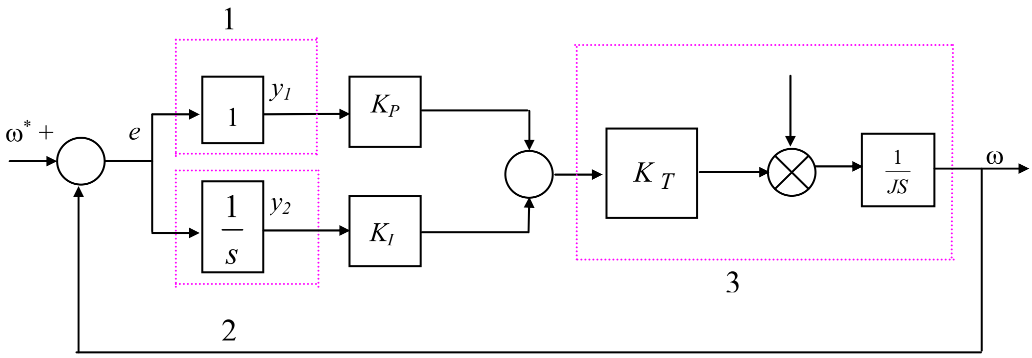


Fig. 2: The design of self-tuning PI for induction motor

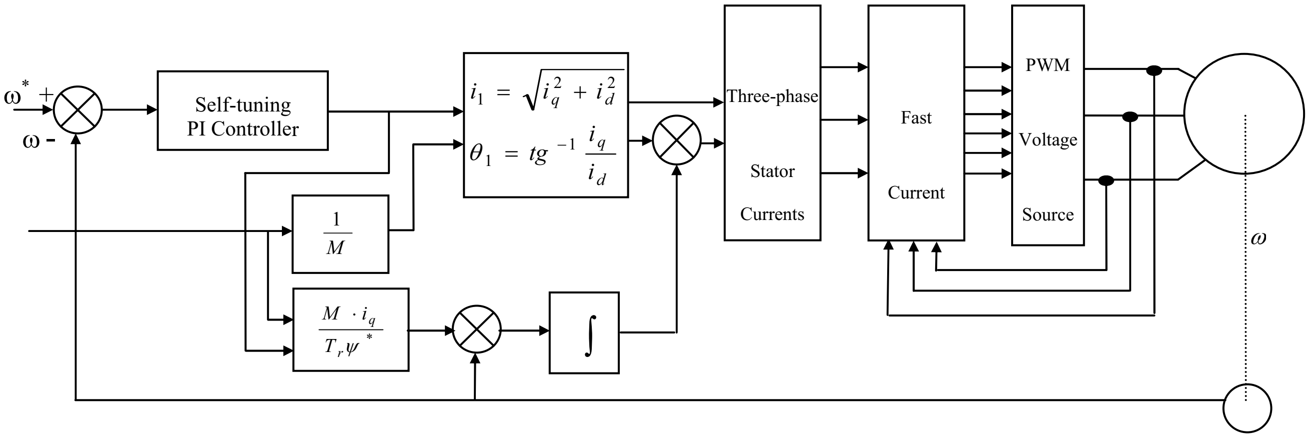


Fig. 3: The whole block diagram of the induction motor drive system

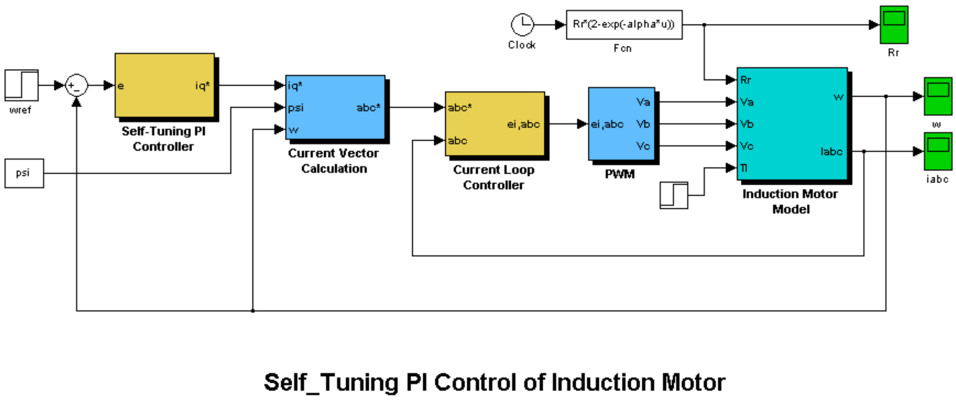


Fig. 4: Matlab/Simulink model of the induction motor drive system

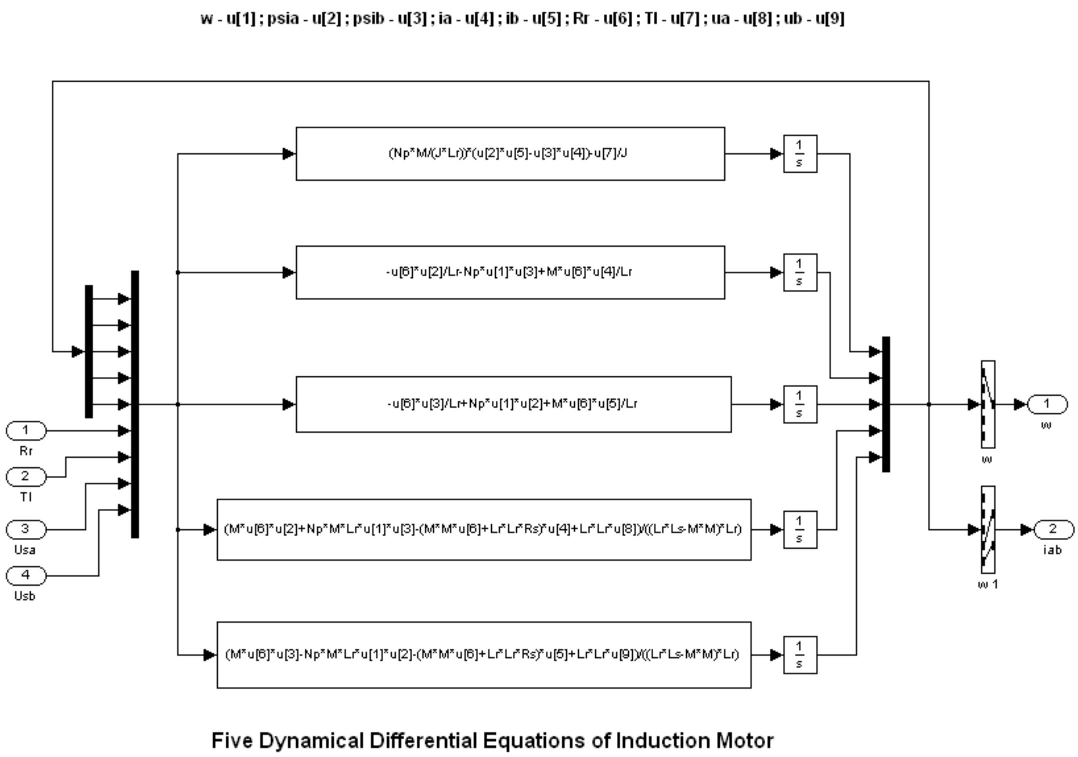
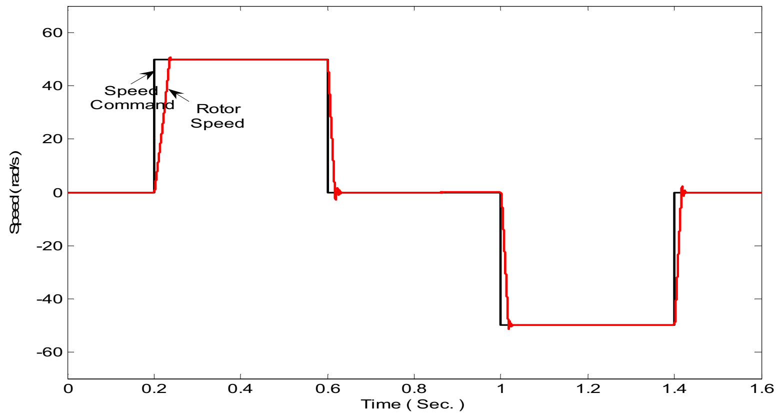
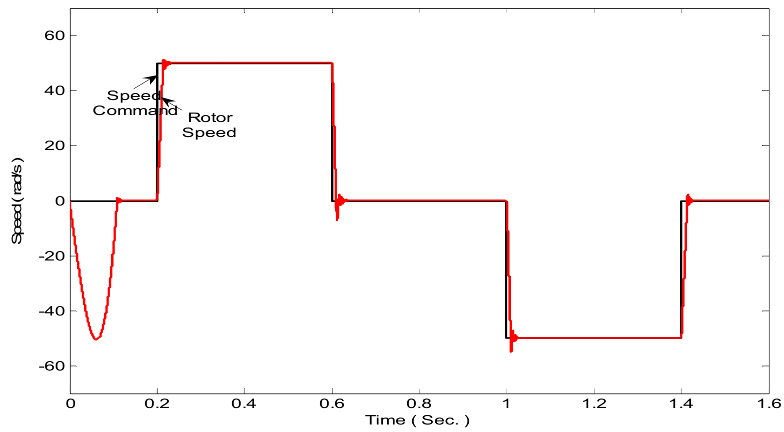


Fig. 5: Simulink model of an induction motor



(a)



(b)

Fig. 6: (a) Speed response in four quadrants without load.
(b) Speed response in four quadrants with 100% load

V. Conclusion

The work of modeling and simulation of an entire induction motor drive system controlled by a self-tuning PI controller has been presented in this paper. In addition a novel detailed Simulink model for induction motor has been illustrated, which allows us to clearly visualize the relationship between the internal parameters and the system performances. By using the computer simulation, it has been found that the proposed design approach is robust to the variations of induction motor parameters and achieves the performance of global asymptotic speed tracking.

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