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Performance of Sliding Mode Control for Three Phase Induction Motor

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***Abstract*—In this paper, sliding mode control (SMC) scheme is employ to three phase induction motor to replace the conventional PI speed control. Indirect field orientation control is used to ensure decoupling control between torque and flux of induction motor. This is realized by using Clarke and Park transformation. The performance of the purposed SMC with integral sliding surface is test under changes in R_s, R_R, L_s, L_r and L_m, and load disturbances in different speed command. The results show that the SMC can give robust performance under parameter uncertainty and external load disturbances. The effectiveness of the purposed scheme is verifying using MATLAB/SIMULINK.**

***Keywords*— Induction motor; indirect field orientation; sliding mode control.**

I. INTRODUCTION

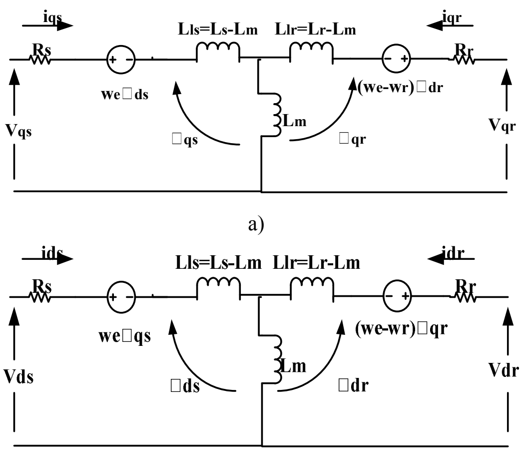
At the present time, the Vector control method or mostly known as field oriented control (FOC) technique is the widespread used in high performance induction motor drives [1, 2]. It allows, by means a co-ordinate transformation, to decouple the electromagnetic torque control from the rotor flux, and hence to manage induction motor as DC motor. In this method, the variables are transformed into a reference frame in which the dynamic behave like dc quantities. The decoupling control between the flux and torque allows induction motor to achieve fast transient response. Therefore, it is preferred used in high performance motor applications.

However, the performance of induction motor will be degraded by motor parameters variation and load disturbances. Conventional field oriented control of induction motor drives with fixed gain controllers (such as PI controllers) fail to provide satisfactory response for trajectory tracking in servo applications [3]. In order to overcome these difficulties, the variable structure control possesses the robustness using sliding mode control was adopted in [3-6] because it has many good features, such as robustness to parameter variations or load disturbances, fast dynamic response, and simplicity of design and implementation [1, 7, 8]. The basic concept and principles of SMC to electrical drives have been demonstrated in [9], and now its becomes one of the perspective control methodology for induction motor drives. Since then, various techniques has been use such as combination of SMC and fuzzy logic [10], adaptive SMC [11] and development of proportional integral sliding mode [12]. In Sliding mode strategy, the drive response is forced to slide along predefined trajectory in a phase plane by switching algorithm. The strategy can be obtained by breaking the design procedures of SMC into two schemes. First, design the sliding surface, and second, control low is chosen so that the system trajectory of the closed loop motion direct towards the surface. There are two type of sliding surface that are well known in the sliding mode control, the conventional sliding surface and proportional integral sliding surface.

This paper presents the performance of the sliding mode control with integral sliding surface when dealing with parameter uncertainty and load disturbances. The investigation of SMC is carried out based on several selected speed respond. The validity of the purposed scheme was demonstrated using MATLAB/SIMULINK.

II. DYNAMIC MODEL OF INDUCTION MOTOR

Three phase squirrel cage induction motor in synchronously rotating reference frame can be represent as figure1.0,[13]



b)
Fig. 1:Equivalent circuit of induction motor in synchronous rotating reference frame; a) q-axis circuit b) d-axis circuit

Where the voltage equation is:

$$V_{qs}=R_s i_{qs}+\frac{d\varphi_{qs}}{dt}+\omega_e\varphi_{ds} \tag{1}$$

$$V_{ds}=R_s i_{ds}+\frac{d\varphi_{ds}}{dt}-\omega_e\varphi_{qs} \tag{2}$$

$$V_{qr}=R_r i_{qr}+\frac{d\varphi_{qr}}{dt}+(\omega_e-\omega_r)\varphi_{dr} \tag{3}$$

$$V_{dr}=R_r i_{dr}+\frac{d\varphi_{dr}}{dt}-(\omega_e-\omega_r)\varphi_{qr} \tag{4}$$

and $V_{qr}\,,V_{dr}=0$, the flux equation:

$$\varphi_{qs}=L_{ls}i_{qs}+L_m(i_{qs}+i_{qr}) \tag{5}$$

$$\varphi_{qr}=L_{lr}i_{qr}+L_m(i_{qs}+i_{qr}) \tag{6}$$

$$\varphi_{ds}=L_{ls}i_{ds}+L_m(i_{ds}+i_{dr}) \tag{7}$$

$$\varphi_{dr}=L_{lr}i_{dr}+L_m(i_{ds}+i_{dr}) \tag{8}$$

where $V_{qr}\,,V_{dr}$ are the applied voltages to the stator, $i_{ds,}\ i_{qs},\ i_{dr},\ i_{qr}$ are the corresponding d and q axis stator current and rotor currents. $\varphi_{qs}, \varphi_{qr}, \varphi_{ds}, \varphi_{dr}$, are the rotor flux component, R_s , R_r are the stator and rotor resistances, L_{ls}, L_{lr} denotes stator and rotor inductances, whereas L_m is the mutual inductance. Combining the flux equation with (1), (2), (3) and (4), the electrical transient model in term of voltage and current can be represents in matrix form as:

$$\begin{bmatrix} v_{qs}\\ v_{ds}\\ v_{qr}\\ v_{dr}\end{bmatrix} = \begin{bmatrix} R_s+SL_s & \omega_e L_s & SL_m & \omega_e L_m\\ -\omega_e L_s & R_s+SL_s & -\omega_e L_m & SL_m\\ SL_m & (\omega_e-\omega_r)L_m & R_r+SL_r & (\omega_e-\omega_r)L_r\\ -(\omega_e-\omega_r)L_m & SL_m & -(\omega_e-\omega_r)L_r & R_r+SL_r\end{bmatrix} \times \begin{bmatrix} i_{qs}\\ i_{ds}\\ i_{qr}\\ i_{dr}\end{bmatrix} \tag{9}$$

where, S is the Laplace operator.

The electromagnetic torque equation given by [13] is

$$T_e=\frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\varphi_{dr}i_{qs}-\varphi_{qr}i_{ds}) \tag{10}$$

where P, denote the pole number of the motor. If the vector control is fulfilled, the q component of the rotor field φ_{qr} would be zero. Then the electromagnetic torque is controlled only by q-axis stator current and becomes:

$$T_e=\frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\varphi_{dr}i_{qs}) \tag{11}$$

III. INDIRECT FIELD ORIENTED CONTROL

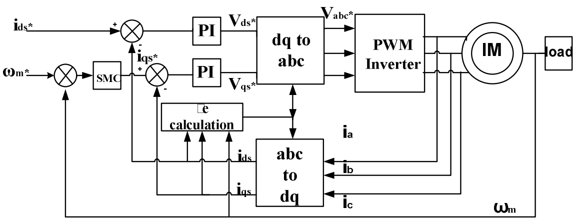


Fig. 2. Indirect field oriented control with SMC

Fig. 2, shows a block diagram of indirect field oriented induction motor drive system. The flux command i_{ds}^* indicates the right rotor flux command for every speed reference within the nominal value. The rotor speed ω_m is compared to rotor speed command ω_m^* and the resulting error is process in the controller. The controller generates the q axis reference current i_{qs}^*. Both d-q axis commands is compared to the d-q axis that obtain from the transformation from (12).

$$\begin{bmatrix} i_{ds}\\ i_{qs}\end{bmatrix} = \begin{bmatrix} cos\theta & \cos(\theta-\frac{2\pi}{3}) & \cos(\theta+\frac{2\pi}{3})\\ -sin\theta & -\sin(\theta-\frac{2\pi}{3}) & -\sin(\theta+\frac{2\pi}{3})\end{bmatrix}\begin{bmatrix} i_a\\ i_b\\ i_c\end{bmatrix} \tag{12}$$

The current regulator output are V_{ds}^* and V_{qs}^*. Through (13) the voltage command V_{ABC}^*gives the input to PWM inverter.

$$\begin{bmatrix} V_a\\ V_b\\ V_c\end{bmatrix} = \begin{bmatrix} cos\theta & -sin\theta\\ \cos(\theta-\frac{2\pi}{3}) & -\sin(\theta-\frac{2\pi}{3})\\ \cos(\theta+\frac{2\pi}{3}) & -\sin(\theta+\frac{2\pi}{3})\end{bmatrix}\begin{bmatrix} V_{ds}\\ V_{qs}\end{bmatrix} \tag{13}$$

In induction motor, the knowledge of rotor flux angular position θ_e is necessary. It can be compute as follows:

$$\theta_e=\int\omega_e dt=\int(\omega_{sl}+\omega_r)dt \tag{14}$$

ω_{sl} is slip frequency and $\omega_r=\frac{p}{2}\omega_m$

and it can be obtained as:

$$\omega_{sl}=\frac{L_m R_r i_{qs}}{\varphi_{dr}L_r} \tag{15}$$

IV. SLIDING MODE CONTROL

Based on complete indirect field orientation, sliding mode control with integral sliding surface is discussed in this section. Under the complete field oriented control, the mechanical equation can be equivalently described as:

$$T_e = K_T i_{qs} \quad (16)$$

where, K_T is the torque constant and defined as follows:

$$K_T = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\varphi_{dr} \quad (17)$$

The mechanical equation of an induction motor can be written as:

$$T_e = J\dot{\omega}_m + B\omega_m + T_L \quad (18)$$

Using (16) into (18), we can obtained

$$bi_{qs} = \dot{\omega}_m + a\omega_m + f \quad (19)$$

Where $a = B/J$, $b = K_T/J$ and $f = T_L/J$

Equation (19) can be represents with uncertainties Δa, Δb and Δf in term a, b and f respectively, as follows:

$$\dot{\omega}_m = -(a + \Delta a)\omega - (f + \Delta f) + (b + \Delta b)i_{qs} \quad (20)$$

The tracking speed error is defined as

$$e(t) = \omega_m(t) - \omega_m^*(t) \quad (21)$$

where ω_m^* is a rotor speed reference. Taking derivative of eq. 21 with respect to time yields:

$$\dot{e}(t) = \dot{\omega}_m(t) - \dot{\omega}_m^*(t) = -ae(t) + u(t) + d(t) \quad (22)$$

where

$$u(t) = bi_{qs} - a\omega_m^*(t) - f(t) - \dot{\omega}_m^*(t) \quad (23)$$

and the uncertainties $d(t)$

$$d(t) = -\Delta a\omega_m(t) - \Delta f(t) + \Delta bi_{qs} \quad (24)$$

The sliding variable S(t) can be defined with integral component as

$$S(t) = e(t) - \int_0^t (k - a)e(\tau)d\tau \quad (25)$$

where k is a constant gain. When the sliding mode occurs on the sliding surface, then $S(t) = \dot{S}(t) = 0$ and therefore the dynamical behaviour of the controlled system can be expressed as:

$$\dot{e}(t) = (k - a)e(t) \quad (26)$$

In order to obtain the speed trajectory tracking, the following assumption has been formulated in [11],

Assumption 1: The k must be chosen so that the term $(k - a)$ is strictly negative and hence $k < 0$, therefore the sliding surface is defined as:

$$S(t) = e(t) - \int_0^t (k - a)e(\tau)d\tau = 0 \quad (27)$$

The variable structure controller is design as:

$$u(t) = ke(t) - \beta sgn(S) \quad (28)$$

where β is a switching gain, S is the sliding variable and sgn(.) is the sign function defined as:

$$sgn\big(S(t)\big) = \begin{cases} 1 & if S(t) > 0 \\ -1 & if S(t) < 0 \end{cases} \quad (29)$$

Assumption 2: the gain β must be chosen so that $\beta \geq |d(t)|$ all the time.

When sliding mode occurs on the sliding surface, then $S(t) = \dot{S}(t) = 0$ and the tracking error converges to zero exponentially. From (23) and (28), the current command i_{qs}^* can be obtained as:

$$i_{qs}^* = \frac{1}{b}[ke - \beta sgn(S) + a\omega_m^*(t) + \dot{\omega}_m^*(t) + f] \quad (30)$$

Therefore the above design sliding mode speed controller resolves the speed tracking problem under parameter uncertainty and load disturbances.

By using Lyapunov function candidate the proof of this theorem is deduce

$$V(t) = 0.5S(t)^2 \quad (31)$$

The first time derivative of (31) is:

$$\dot{V}(t) = S(t)\dot{S}(t) = S(t)[\dot{e}(t) - (k - a)e(t) \quad (32)$$

Substituting (26) into (28), then;

$$\begin{aligned} \dot{V}(t) &= S(t)[-\beta sgn(S) + d(t)] \\ &= -\beta|S(t)| + d(t)S(t) \\ &\leq -\beta|S(t)| + |d(t)||S(t)| \\ &\leq -[\beta - |d(t)||S(t)| \leq 0 \end{aligned} \quad (33)$$

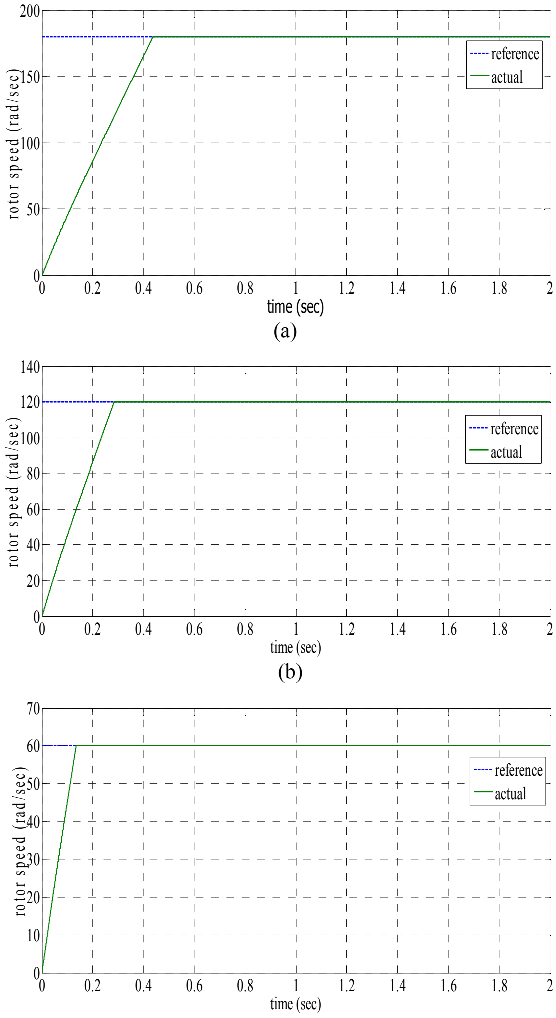
Using assumption 2, it is prove that (33) is not positive, then the sliding mode reaching condition is satisfied.

V. SIMULATION RESULT

For the purpose scheme, a numerical simulation has been carried out by using MATLAB/SIMULINK. The parameters of induction motor used in this drive system are:

1.5KW, 180 rad/sec
R_s, stator resistance, 7.83Ω
R_r, rotor resistance, 7.55Ω
L_s, stator inductance, 0.4751H
L_r, stator inductance, 0.4751H
L_m, magnetizing inductance, 0.4535H
J, moment of inertia, 0.06Kg m^2
B, viscous friction coefficient, 0.01Nm/(rad/s)
P, number of poles,4
φ_{dr}^* is set to 1Wb

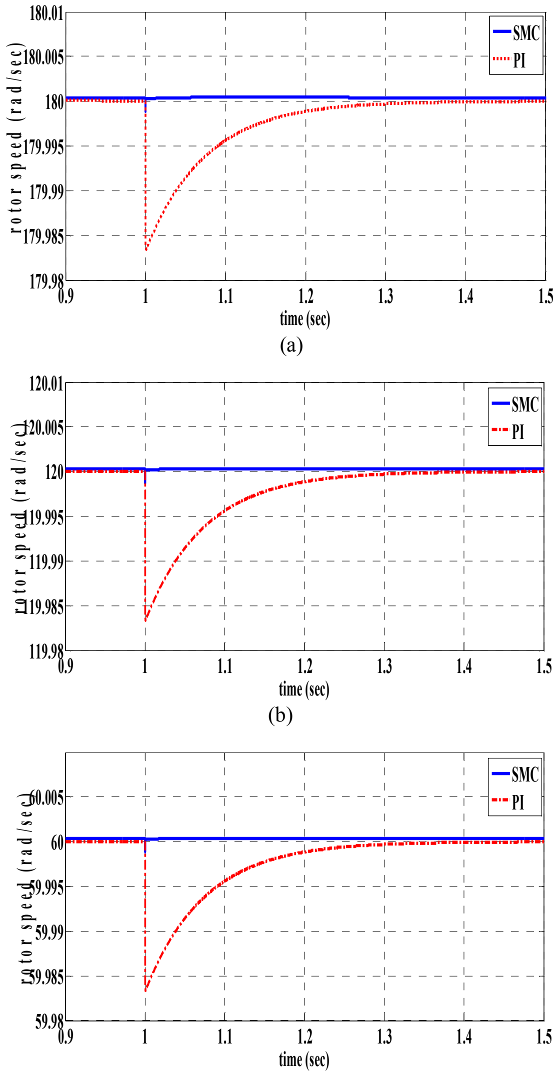
The system is considered under three selected speed command: at rated speed, 180 rad/second, two third of rated speed, 120 rad/second and one third of rated speed, 60 rad/second. Figure 3 (a), (b) and (c) show the speed response during transient and steady state at no load conditions. At rated speed, the system reach steady state at 0.438 second, at two third of rated speed, the system reach steady state at 0.285 second and at one third of rated speed, the system reach steady state at 0.136 second. It is shows that the purpose controllers can response well under high speed and low speed condition without overshoot and undershoot condition.



(c)

Fig. 3: Rotor tracking performance when T_L=0 at different speed, (a) at rated 180 (rad/sec), (b) at 120(rad/sec), (c) at 60 (rad/sec)

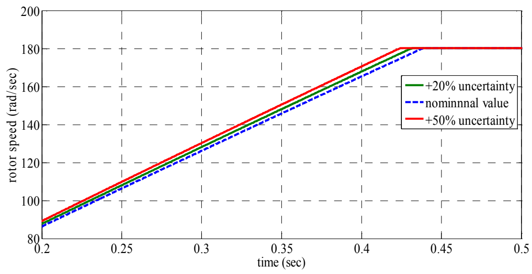
To test the robustness of the controller under load condition, figure 4 (a), (b) and (c) shows the zoomed speed response when load 10 Nm is applied at 1 second for purposed speed controller and conventional PI speed controller at three different speed commands. It shows that the purposed controller maintain robust for the three speed condition. While with PI speed controller, it is shows that the speed is drop about 1.4 percent from the steady state condition at 1 second and takes 0.3 second to recovery.



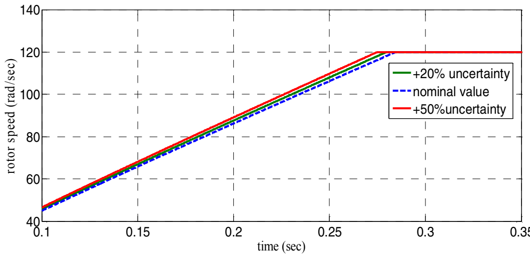
(c)

Fig. 4. Comparison speed response obtain when 10Nm load applied to the system at one second for SMC and PI (a) at rated 180 (rad/sec), (b) at 120(rad/sec), (c) at 60 (rad/sec)

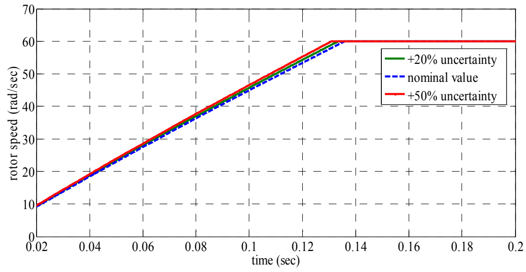
The result for figure 5 (a), (b) and (c) shows the zoomed performance of the rotor speed by increasing twenty percent and fifty percent from the rated R_s, R_r, L_r, L_s and L_m at three different speed command. It is shows that a small difference in reaching steady state occurs. In Fig. 5(a), a difference of 0.014 second occurs at 50 percent uncertainties and 0.009 second occurs at 20 percent uncertainties when compare to nominal speed respond. The same effects happen at Fig 5(b) and (c), only a small difference occurs when compares to nominal respond. It can be seen that parameter variation does not allocate the performance of the purposed control. The system maintain robust to parameter variation.



(a)



(b)



(c)

Fig. 5: Speed response for additional 20and 50 percent uncertainty (a) at rated 180 (rad/sec), (b) at 120(rad/sec), (c) at 60 (rad/sec)

Next, forward and reverse operation is tested to the induction motor as shown in figure 6. The speed command is increased linearly from 0 to 180 rad/sec at 0.5 second. It is kept constant at 180 rad/sec until 1.5 second and decreased linearly to -180 rad/sec at 2.53 second. Then the speed command is remain constant at -180 rad/sec until it reach 3.5 second and increased linearly to zero at 4 second. Load torque of 10Nm is applied from 0.75 second to time 1.25 second and -10Nm is applied from time 2.75second to 3.25 second. While, figure 7 shows conversely of the system. It is obviously shows that the system can manage both in forward and reverse operation even with additional load disturbances. The system shows that there are no overshoot and undershoot and negligible of steady state error.

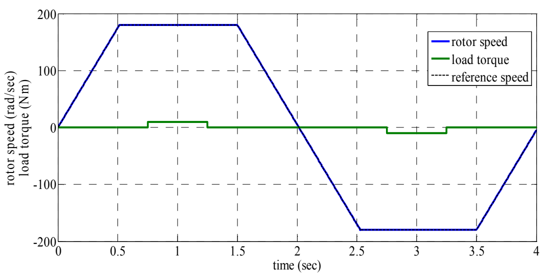


Fig. 6: Speed responses during forward and reverse operation by applied and eliminate load at rated speed

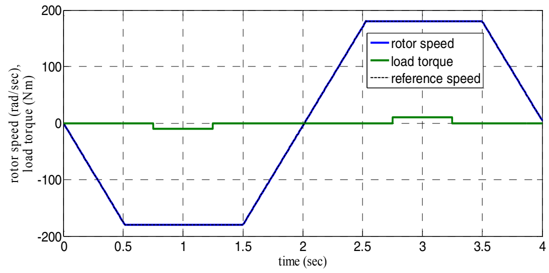


Fig. 7: Speed responses during reverse and forward operation by applied and eliminate load at rated speed

Based on above results obtained, it can be seen that the SMC can provide robust performance. By means of simulation examples, it has been shown that the proposed control scheme performs reasonably well in practice, and that the speed tracking objective is achieved under uncertainties in the parameters and load disturbances.

VI. CONCLUSION

A sliding mode control with integral sliding surface for high performance induction motor has been developed for this paper. Using indirect field orientation, it is ensure to control torque and flux separately. From the simulation result, it is show that the control system has good performance and robust against parameter variation and load disturbances.

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