Design and Performance Analysis of Speed Controller in Induction Motor with Sliding Mode Control

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Abstract— ***Sliding Mode Control*** **(SMC) is implemented in this research to control the speed of induction motor. The robust superiority of SMC in anticipating disturbance uncertainty and non linear characteristic of induction motor is achieved by first designing a sliding surface and computing the related control signal that are current, flux and speed. An addition of a boundary layer is used to wash out the chattering phenomena. As a result, beside robust performance against disturbance at various operating conditions, the controller proposed here has fast response following induction motor speed dynamics under investigation.**

Keywords-induction motor; sliding mode controlt; speed controller; disturbance uncertainty.

I. INTRODUCTION

Induction motor has many applications in industries because of its simple construction, cheap, easy in maintenance, reliable and high efficiency. Unfortunately it has several drawbacks such as speed control which is not as simple as DC Machine and also its efficiency changes with load and speed variety [1].

Modern industry require high performance of induction machine especially accurate speed variation following to variable load and should also robust against disturbance dynamics[2]. Therefore a controller is needed to regulate the speed according to the demand while keeping good efficiency performance.

In this paper sliding mode control will be implemented to design the speed controller by choosing a sliding surface in the form of state space inside a specific closed loop system dynamics. Switching and control law function were designed in a way so that the state trajectory achieve and move on the surface. The superiority of this method is its robustness against disturbance and model uncertainty and also more less information is needed compared to the classical controller. Because of those superiority, it is especially useful when implemented for very non linear system [3,5,7].

II. BASIC THEORY

In general, induction motor speed controller block diagram is as follows:

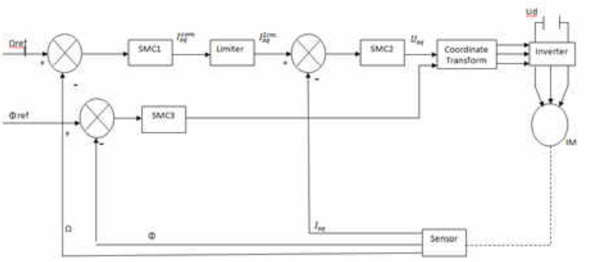

Figure 1.Blok Diagram Induction Motor Speed Controlled

A. Induction Motor Dynamic Model

Three Phase Squirrel Cage Induction Motor Dynamic Model in the d-q axis assuming $\Phi_{rd} = \Phi_r$ dan $\Phi_{rq} = 0$ can be expressed as follows [1,6]:

$$\dot{I}_{sd} = -\gamma I_{sd} + \omega_s I_{sq} + \frac{K}{T_r}\Phi_{rd} + \frac{1}{\sigma L_s}U_{sd} \quad (1)$$

$$\dot{I}_{sq} = -\omega_s I_{sd} - \gamma I_{sq} - P\Omega K\Phi_{rd} + \frac{1}{\sigma L_s}U_{sq} \quad (2)$$

$$\dot{\Phi}_{rd} = M_{sr}I_{sd} - \frac{1}{T_r}\Phi_{rd} \quad (3)$$

$$\dot{\Phi}_{rq} = \frac{M_{sr}}{T_r}I_{sq} - (\omega_s - P\Omega)\Phi_{rd} \quad (4)$$

$$\dot{\Omega} = \frac{PM_{sr}}{JL_r}(\Phi_{rd}I_{sq}) - \frac{C_r}{J} - f\Omega \quad (5)$$

with:

$$T_r = \frac{L_r}{R}; \sigma = 1 - \frac{M_{sr}^2}{L_s L_r};$$

$$K = \frac{M_{sr}}{\sigma L_s L_r}; \ \gamma = \frac{R_s}{\sigma L_s} + \frac{R_r M_{sr}^2}{\sigma L_s L_r^2}$$

Φ_{rd}, Φ_{rq} is rotor flux component ; U_{sd}, U_{sq} is stator voltage component; I_{sd}, I_{sq} is stator current component; σ is leak factor; p is pole number; R_s and R_r are stator and rotor resistances; L_s and L_r are stator and rotor induktances; M_{sr} is mutual induktance; T_e is electromagnetic torque; C_r is load torque, J is induction motor inertia moment; Ω is mechanic speed; ω_s is stator pulsation; f is damping coefisien and T_r is rotor time constant.

B. Sliding Mode Control

Sliding Mode is a technique to regulate the feedback by firstly defining a surface. Controlled system (variables) will be moved to the surface and system motion is directed to equilibrium point desired.

Look at to a dynamic system [4]:

$$x^{(n)} = f(x) + b(x)u \tag{6}$$

where u is a control input, and $x = \begin{bmatrix} x & \dot{x} & \ldots & x^{(n-1)} \end{bmatrix}^T$ is a space vector while f(x) and b(x) are limited functions. If x_d is the desired , then its tracking error is:

$$e = x_d - x \tag{7}$$

Sliding surface is defined as [5,8]

$$S(x,t) = 0 \tag{8}$$

with

$$S(x,t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} \tag{9}$$

λ is positive coefficient and *n* is system orde. The above equations are used to result system output that converge to the desired output.

Then a control law :

$$u = u_{eq} + m\,\mathrm{sgn}(S) \tag{10}$$

is determined as new control input with equivalent control signal u_{eq} was gained from $\dot{S} = 0$. Control gain *m* was determined from sliding condition:

$$S\dot{S}\langle \eta |S| \tag{11}$$

III. METHOD

A. Speed Controller Design

Tracking error of the speed state is

$$e_1 = \Omega_d - \Omega$$

and

$$\dot{e}_1 = \dot{\Omega}_d - \dot{\Omega}$$

For speed state, (9) result switching function S_1

$$S_1 = \Omega_d - \Omega \tag{12}$$

Because the sliding surface S_1 = 0, then (12) can be written as

$$\Omega_d - \Omega = 0 \tag{13}$$

From (13), the first derivative of S_1 can be written as

$$\dot{S}_1 = \dot{\Omega}_d - \frac{PM_{sr}}{JL_r} \Phi_{rd} I_s \tag{14}$$

and

$$I_{sq}^{eq} = \frac{JL_r}{PM_{sr}\Phi_{rd}} \left(\dot{\Omega}_d + \frac{c_r}{J} + \frac{f}{J}\Omega\right) \tag{15}$$

To reduce the chattering, the following control term is used.

$$I_{sq}^{n} = m_1 sat\left(\frac{S_1}{\varphi_1}\right) \tag{16}$$

with

$$\varphi_1 = 1$$

From (15) and (16) a new control input value was resulted as follows:

$$I_{sq} = \frac{JL_r}{PM_{sr}\Phi_{rd}} \left(\dot{\Omega}_d + \frac{c_r}{J} + \frac{f}{J}\Omega\right) + m_1 sat\left(\frac{S_1}{\varphi_1}\right) \tag{17}$$

B. Current Controller Design

This controller is designed to limit the possibility of current overshoot. Current limitation is defined [1]:

$$I_{sq}^{\lim} = I_{sq}^{\max} sat I_{sq}^{com}$$

Switching function for current controller is

$$S_2(I_{sq}) = I_{sq}^{\lim} - I_{sq} \tag{18}$$

and

$$\dot{S}_2(I_{sq}) = \dot{I}_{sq}^{\lim} - \dot{I}_{sq} \tag{19}$$

Substitute (2) into (15) :

$$\dot{S}_2(I_{sq}) = \dot{I}_{sq}^{\lim} + \omega_s I_{sd} + \lambda I_{sq} + P\Omega K \Phi_{rd} - \frac{1}{\sigma L_s} U_{sq} \tag{20}$$

The resulted equivalent control U_{sq}^{eq} :

$$U_{sq}^{eq} = \sigma L_s \left(\dot{I}_{sq}^{\lim} + \omega_s I_{sd} + \gamma I_{sq} + P\Omega K \Phi_{rd}\right) \tag{21}$$

Control term for current controller is

$$U_{sq}^{n} = m_2 sat\left(\frac{S_2}{\varphi_2}\right)$$

with

$$\varphi_2 = 1$$

Then

$$U_{sq} = U_{sq}^{eq} + U_{sq}^{n} \tag{22}$$

C. Rotor Flux Controller Design

Tracking error for *state* Φ_{rd} is

$$e_3 = \Phi_{rd}^{ref} - \Phi_{rd}$$

The derivative of $\dot{e}_3$ is

$$\dot{e}_3 = \dot{\Phi}_{rd}^{ref} - \dot{\Phi}_{rd}$$

Switching function S_2 can be derived as follows

$$S_3 = \dot{\Phi}_{rd}^{ref} - \dot{\Phi}_{rd} + \lambda\Phi_{rd}^{ref} - \lambda\Phi_{rd} \quad (23)$$

Because Φ_{rd}^{ref} is constant then $\dot{\Phi}_{rd}^{ref} = 0$ and $\ddot{\Phi}_{rd}^{ref} = 0$ and the equivalent control can be determined as:

$$U_{sd}^{eq} = \sigma L_s \gamma I_{sd} - \sigma L_s \omega_s I_{sq} - \frac{\sigma L_s K}{T_r}\Phi_{rd} + \frac{\sigma L_s(\frac{1}{T_r} - \lambda)}{T_r}\dot{\Phi}_{rd} \quad (24)$$

From control law at (10), the value of new input control U_{sd} is

$$U_{sd} = \sigma L_s \gamma I_{sd} - \sigma L_s \omega_s I_{sq} - \frac{\sigma L_s K}{T_r}\Phi_{rd} + \frac{\sigma L_s(\frac{1}{T_r} - \lambda)}{T_r}\dot{\Phi}_{rd}$$
$$+ m_3 sat(S_3)$$

The values m_1, m_2, and m_3 are designed to fulfill sliding condition at (11)

$$S\dot{S} \le -\eta|S|$$

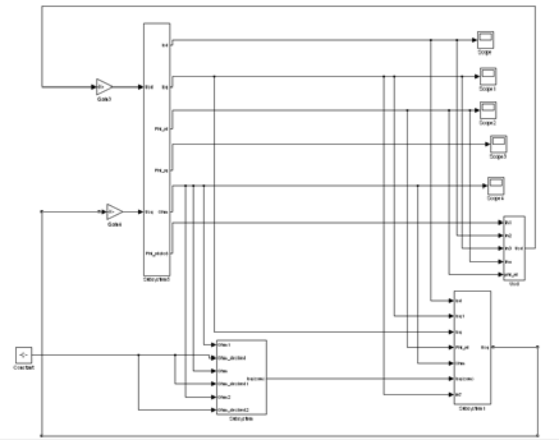

Figure 2. Block diagram of induction motor plant with SMC controller in Simulink Matlab

IV. RESULT

Block diagram of SMC controller together with induction motor plant in Simulink is shown at Fig. 2. Induction motor used has the specification of 0.75 kW, 220 V, 50 Hz. Simulation was conducted using the following parameter values: R_s = 0.63Ω; R_r =0.4Ω; L_s = 0.105H; L_r = 0.094H; M_{sr} = 0.094H; J = 0.0256 Kgm^2; f = 0.001 Nms/rad [1].

Fig. 3 is the response of machine flux before being controlled and without internal disturbance. Flux State has delay time 1.3 s and rising time 2.85 s. Flux stable at 0.15 Wb at 4 s. It is shown that flux response is stable enough with negligible overshoot.

Fig. 4 show the response of induction motor speed before being controlled and without internal disturbance. Speed state has a final value about 3.31 rpm, delay time 1.45 s and rise time 0.78 s. There is an overshoot with peak time 2.3, maximum overshoot 2.31 and settling time 4.36 s.

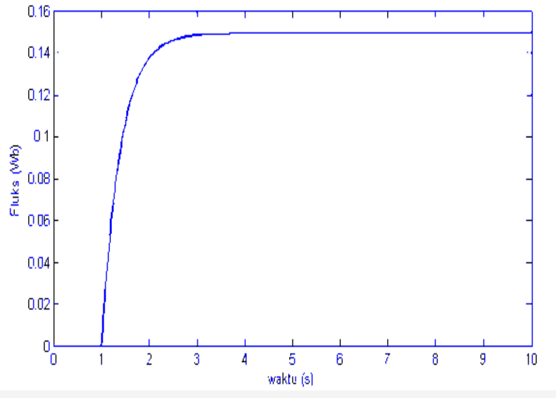

Figure 3. Flux response

When SMC controller installed and it is desired that the flux has a value of 0,9 Wb without any internal disturbance then the resulting simulation of flux response are like at Figure 5.

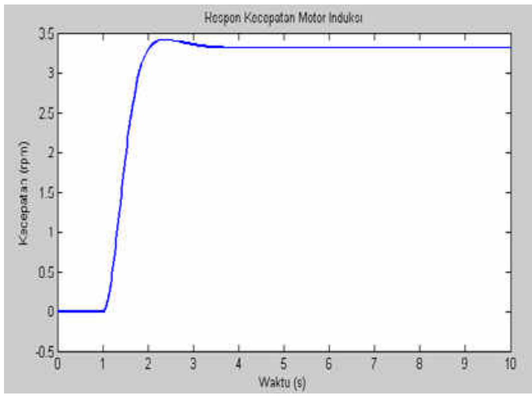

Figure 4. Speed response

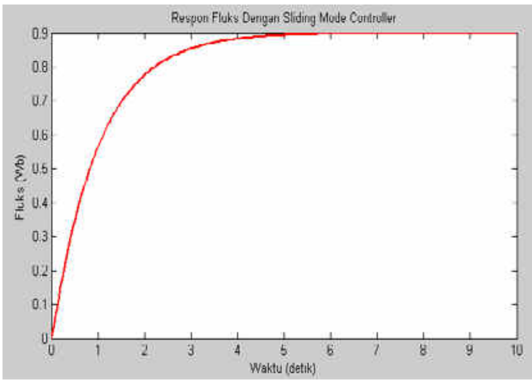

Figure 5. Flux Response with SMC

Fig. 5 shows flux response after being controlled. It is seen that flux state has no overshoot with settling time 5.5 s, rise time 7 s, and delay time 0.7 s which 0.5 s faster compared with before being controlled.

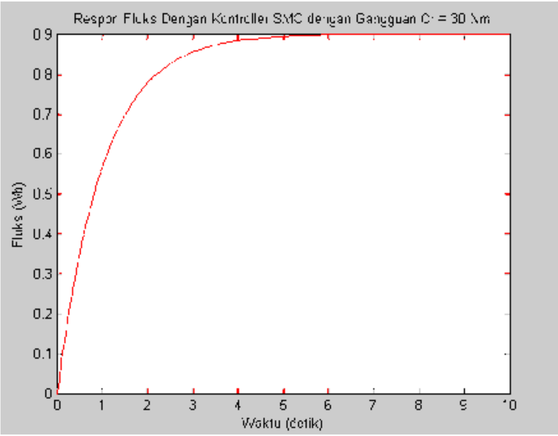

Figure 6. Flux Response with SMC Under Cr=30Nm

Fig. 6 shows the response of flux after being controlled under 30 Nm disturbances. It is shown that the *delay time* now is 0.7 s same with the result before being controlled. The rise time is 7.75 s which is 0.75 s slower compared to the condition before being controlled. The settling time is 7.75 s, 2.25 s slower compared with the result before being controlled. From the transient result, it can be concluded that the disturbance make the system speed response slower.

Another simulation result without internal disturbance with reference speed at 1000 rpm give the results of speed as shown at Fig. 7.

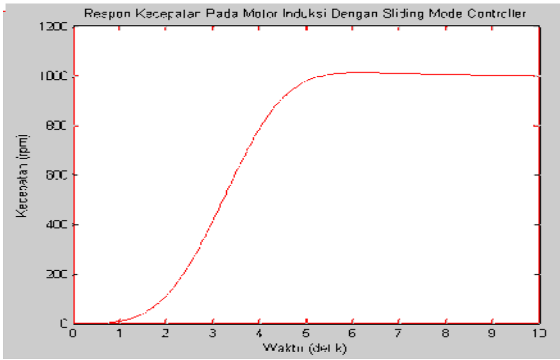

Figure 7. Speed Response on Induction Motor Speed with SMC Without Any Disturbance

The result of controlled speed response at Fig. 7 shows a delay time of 3.24 s, rise time 2.9 s, settling time 6 s, with negligible overshoot.

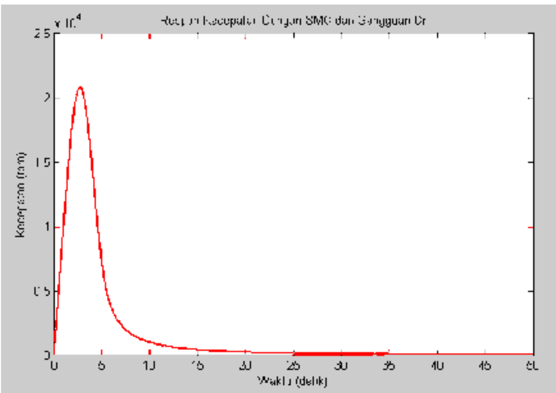

Figure 8. Speed Response With SMC and Disturbance Cr 30 Nm

Fig. 8 shows the speed response of the SMC controlled system under internal disturbances Cr= 30 Nm. It can be seen the disturbance cause significant overshoot. High overshoot caused by high disturbance. In the real application the disturbance value about 3 Nm is quite normal. It also shows the results of peak time 2.75 s, delay time 0.05 s, rising time 10.475 s, and settling time 10 s. It can be concluded that the existence of the disturbance cause slower convergence.

The robustness of the proposed Sliding Mode Control is tested by changing the rotor resistance value to be 0.36 Ω. The simulation result for flux response under this condition is shown at Fig. 9. From the figure, the delay time is 0.7 s, rise time 6 s, settling time 6 s and the system is stable. It can be concluded from the simulation that the uncertainty of the parameter until 10% can be adopted by the controller.

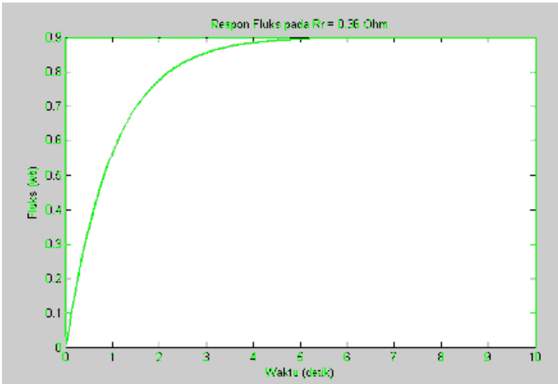

Figure 9. Induction Motor Speed Response with R_r

V. CONCLUDING REMARK

The Proposed SMC Controller can be implemented for controlling the flux and speed of non linear modeled induction motor under parameter uncertainty until 10%.

The use boundary layer inside the SMC was proved to be useful in reducing the chattering phenomena.

Beside the robustness under 10 % parameter changes, the proposed controller speed performance gives faster response until 40 % compared with the condition without controller.

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