

Application of Sliding Mode Control in Indirect Field Oriented Control (IFOC) for Model Based Controller

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Abstract

Indirect Field Oriented Control (IFOC) is one of the vector control methods that can be applied to induction motor in the industrial world rather than Direct Field Oriented Control (DFOC) because of the flux is obtained from the formulation. However, IFOC can not guarantee the robustness and stability of the systems. Stability analysis such as Lyapunov Stability Theory can be used to make the system stable but not the robustness. Model based controller that can guarantee the stability and robustness such as sliding mode control (SMC) and fuzzy needs to be added in IFOC system to achieve proportional response system. Robust current regulator using sliding mode control was designed in this paper from state space model for model based controller. In transient response and under disturbance SMC shows better performance than PID in rising time and robustness at rotor speed and stator current.

Keyword : IFOC, Induction Motor, State Space Equation, Model Based Controller, SMC.

NOMENCLATURE

Voltage	(V)	220	Volt
Frequency	(f)	50	Hz
Rotor Type		Squirrel Cage	
Rotor Resistance	(R_r)	6.085	Ω
Stator Resistance	(R_s)	6.03	Ω
Rotor Inductance	(L_r)	0.4893	H
Stator Inductance	(L_s)	0.4893	H
Mutual Inductance	(L_m)	0.4503	H
Number of Pole Pairs	(P)	2	
Moment of Inertia	(J)	0.00488	Kg

1. INTRODUCTION

Induction motors are widely used in the industrial world for their firm and low price [1]. Vector control method in induction motors can provide high dynamic performance. IFOC which is one part of the vector control method can be applied and accepted by the electric drive market in an industrial world [2],

[3], [4]. However, IFOC cannot guarantee robustness and stability aspect of the systems. Robustness and stability aspects must be added to achieve high-performance of the system. The analytical stability such as Lyapunov Stability Theory can guarantee the stability of the system but not the robustness.

Model based controller such as fuzzy [5], [6] and sliding mode control (SMC) [7], [8] can be designed to guarantee robustness, stability and optimal condition of the system. State space equation should be modelled to determine the architecture of the controller such as fuzzy and SMC. The IFOC state space equation is obtained from the modeling of the induction motor at DQ rotating frame by making the flux on the d-axis to be constant and the q-axis to zero [3].

This paper is organized as follows. Section 2 describes about related research with this issue. The originality of this paper is shown in section 3. Section 4 describes per unit induction motor model in the rotating frame with arbitrary speed. The way to get IFOC equation from induction motor model in DQ reference frame is described in section 5. In section 6, the IFOC equations that consist of speed, flux, and current regulator equation is modeled to state space can be used to design the model based controller. In section 7, IFOC – SMC design is proposed to make response system robust and stable. Result and discussion about rotor speed and current regulator response in IFOC state space are described in section 8. Finally, the conclusions of this paper are shown in section 9.

2. RELATED WORKS

I F O C is one of the vector control methods that separate torque and flux in the induction motor. This technique represents the complex and nonlinear model of induction motor in a similar manner to DC machines to get high-performance control [3]. The basic characteristic of flux, speed and stator current of IFOC need the controller to perform good characteristic, guarantee robustness and stability .

The model based controller like fuzzy model based and sliding mode control need a state space model to generate controller design. The state space model can be used to determine the stability condition using stability theory such as lyapunov and the constant of robustness to perform proportional response system [9].

Research about the robust controller for speed regulation using sliding mode for IFOC system already exists. In this research, the sliding mode controller is designed in speed regulation to guarantee the robustness in rotor speed aspect [10]. This paper proposed the design of IFOC state space for induction motor in a current regulator. The state space can be used to design the suitable controller that guarantee robustness, stability, and high-performance in dynamic response. The sliding mode is designed in current regulator side to guarantee the robustness in speed response.

3. ORIGINALITY

This paper contribution is designing sliding mode control (model-based controller) for IFOC which applied for an induction motor. The sliding mode is designed in current regulator side to achieve the robustness, stability and reach the optimal condition in proportional time of rotor speed. The chattering phenomenon in rotor side should be avoided because of its danger to the hardware and consume more energy. By designing SMC in current regulator, the chattering phenomenon in rotor speed can be eliminated but not the robustness and stability.

4. INDUCTION MOTOR MODEL

Per phase of induction motor's equivalent circuit consist of stator and rotor side resistance, leakage inductance, induced voltage and mutual inductance shown in Figure 1.

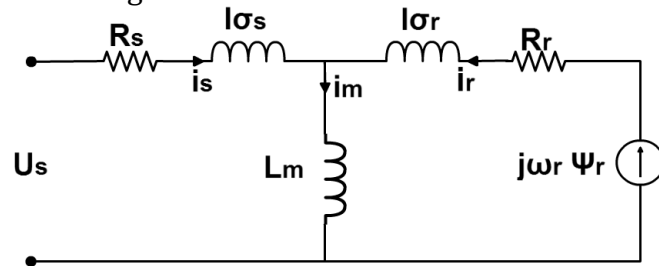


Fig. 1. Per phase equivalent circuit of IM

The induction motor model presented in the rotating frame with arbitrary reference speed is [3], [11] :

$$\left\{ \begin{aligned} \frac{di_{sx}}{d\tau} &= \frac{R_s L_r^2 + R_r L_m^2}{L_r w} i_{sx} + \frac{R_s L_m}{L_r w} \psi_{rx} + \omega_k i_{sy} + \omega_r \frac{L_m}{w} \psi_{ry} + \frac{L_r}{w} U_{sx} \\ \frac{di_{sy}}{d\tau} &= \frac{R_s L_r^2 + R_r L_m^2}{L_r w} i_{sy} + \frac{R_s L_m}{L_r w} \psi_{ry} - \omega_k i_{sx} - \omega_r \frac{L_m}{w} \psi_{rx} + \frac{L_r}{w} U_{sy} \\ \frac{d\psi_{rx}}{d\tau} &= -\frac{R_r}{L_r} \psi_{rx} + \omega_{sl} \psi_{ry} - R_r \frac{L_m}{L_r} i_{sx} \\ \frac{d\psi_{ry}}{d\tau} &= -\frac{R_r}{L_r} \psi_{ry} + \omega_{sl} \psi_{rx} - R_r \frac{L_m}{L_r} i_{sy} \\ \frac{d\omega_r}{d\tau} &= \frac{L_m}{J L_r} (\psi_{rx} i_{sy} - \psi_{ry} i_{sx}) + \frac{1}{J} t_o \end{aligned} \right. \tag{1}$$

where :

$$w = \sigma L_r L_s = L_r L_s - L_m^2$$

$$\sigma = 1 - \frac{L_m^2}{L_r L_s}$$

U_s is voltage and i_s is current of stator vectors; ψ_r is flux of rotor vectors (x, y are real and imaginary axis); ω_r is rotor angular speed; ω_{sl} is slip angular speed; ω_k is angular speed of reference frame; t_o is load torque and τ is relative time [11].

5. INDIRECT FIELD ORIENTED CONTROL (IFOC)

From induction motor model in equation 1, electrical induction motor model in dq rotating frame is [3], [12]:

$$\begin{aligned} \frac{di_{sd}}{dt} &= \frac{1}{\sigma L_s} \left[-R_{sm} i_{sd} + \omega_s \sigma L_s i_{sq} + \frac{L_m}{L_r} \left(\frac{\psi_{rd}}{T_r} + \omega_r \psi_{rq} \right) + U_{sd} \right] \\ \frac{di_{sq}}{dt} &= \frac{1}{\sigma L_s} \left[-R_{sm} i_{sq} + \omega_s \sigma L_s i_{sd} + \frac{L_m}{L_r} \left(\frac{\psi_{rq}}{T_r} + \omega_r \psi_{rd} \right) + U_{sq} \right] \\ \frac{d\psi_{rd}}{dt} &= \frac{L_m}{T_r} i_{sd} + \omega_{sl} \psi_{rq} - \frac{1}{T_r} \psi_{rd} \\ \frac{d\psi_{rq}}{dt} &= \frac{L_m}{T_r} i_{sq} + \omega_{sl} \psi_{rd} - \frac{1}{T_r} \psi_{rq} \end{aligned} \quad (2)$$

where $R_{sm} = R_s + \frac{L_m^2}{L_r^2} R_r$; $\omega_s = \frac{120f}{p}$ and $\omega_{sl} = \omega_s - P\omega_r$; $T_r = L_r/R_r$ is rotor time constant; $\sigma = 1 - \frac{L_m^2}{(L_s + L_r)}$ is total leakage factor.

The mechanical modeling from equation 1 is given by :

$$\frac{d\omega_r}{dt} = \frac{L_m}{JL_r} (\psi_{rd} i_{sq} - \psi_{rq} i_{sd}) + \frac{1}{J} t_o \quad (3)$$

Indirect field oriented control of induction motor's principle is that dq rotating frame is connected to the rotor flux vector. So, the flux and torque can be controlled separately by stator direct-axis current (i_{sd}) and quadrature-axis current (i_{sq}) shown in Figure 2. This form takes the control of an induction motor looks like separately-excited DC motor in linearity control, decoupling and high performance [11], [13], [14].

The field oriented control orientation is obtained by [3], [12] :

$$\begin{cases} \psi_{rd} = \psi_r \\ \psi_{rq} = 0 \end{cases} \quad (4)$$

The current regulator equation can be defined by substitution equation (4) to equations (2) :

$$\begin{aligned} \frac{di_{sd}}{dt} &= \frac{1}{\sigma L_s} \left[-R_{sm} i_{sd} + \omega_s \sigma L_s i_{sq} + \frac{L_m}{L_r} \left(\frac{\psi_r}{T_r} \right) + U_{sd} \right] \\ \frac{di_{sq}}{dt} &= \frac{1}{\sigma L_s} \left[-R_{sm} i_{sq} + \omega_s \sigma L_s i_{sd} + \frac{L_m}{L_r} (\omega_{sl} \psi_r) + U_{sq} \right] \end{aligned} \quad (5)$$

The transformation to make ABC frame to dq0 reference frame is clarke-park transform [2], [3], [11]. The equation for stator current is :

$$\begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{s0} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\gamma_s) & \cos(\gamma_s - 120^\circ) & \cos(\gamma_s + 120^\circ) \\ \sin(\gamma_s) & \sin(\gamma_s - 120^\circ) & \sin(\gamma_s + 120^\circ) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} i_{sA} \\ i_{sB} \\ i_{sC} \end{bmatrix}$$

with :

$$\gamma_s = \int_0^t (P\omega_r + \omega_{sl}) dt$$

where ω_r , ω_s is rotor and stator angular speed of induction motor [10].

The rotor flux in direct axis based on equation 2 substituted to equation 4 is :

$$\frac{d\psi_r}{dt} = \frac{L_m}{T_r} i_{sd} - \frac{1}{T_r} \psi_r \quad (6)$$

equation 6 can be write :

$$\psi_r = \frac{L_m i_{sd}}{1 + T_r s}$$

and the quadrature rotor flux is :

$$0 = \frac{L_m}{T_r} i_{sq} + \omega_{sl} \psi_r - \frac{1}{T_r} \psi_r \quad (7)$$

the mechanical equation substituted from equation 3 to equation 4 is :

$$\frac{d\omega_r}{dt} = \frac{L_m}{JL_r} (\psi_r i_{sq}) + \frac{1}{J} t_o \quad (8)$$

the electromagnetic torque is [11], [15] :

$$T_e = \frac{m_s}{2} P \frac{L_m}{L_r} (\psi_r i_{sq}) \quad (9)$$

where m_s is the number of phase windings.

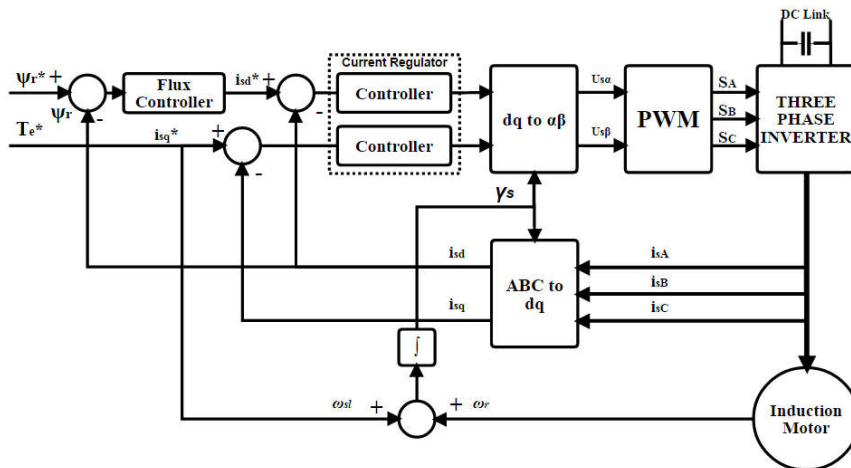


Fig. 2 Indirect field oriented control scheme

6. CURRENT REGULATOR STATE SPACE MODEL OF IFOC

The state space of IFOC shown in Figure 3 uses multiloop model (decoupled / cascade system) which consists of two loops. The inner loop is stator current regulator and the outer loop is rotor flux and speed controller. The state space model of IFOC’s current regulator is :

$$\dot{x} = Ax + Bu + C\psi_r \tag{10}$$

with :

input vector (u) $[U_{sd}, U_{sq}]^T$

state vector (x) $[i_{sd}, i_{sq}]^T$

where :

$$A = \begin{bmatrix} \frac{-R_{sm}}{\sigma L_s} & \omega_s \\ \omega_s & \frac{-R_{sm}}{\sigma L_s} \end{bmatrix}$$

$$B = \begin{bmatrix} 1/\sigma L_s & 0 \\ 0 & 1/\sigma L_s \end{bmatrix}$$

$$C = \begin{bmatrix} \frac{L_m}{L_r T_r} \\ \frac{L_m \omega_{sl}}{L_r} \end{bmatrix}$$

The outer loop equations are rotor flux and speed as in equation 6 and 8

with :

input vector $[i_{sd}, i_{sq}]^T$

state vector $[\omega_r, \psi_r]^T$

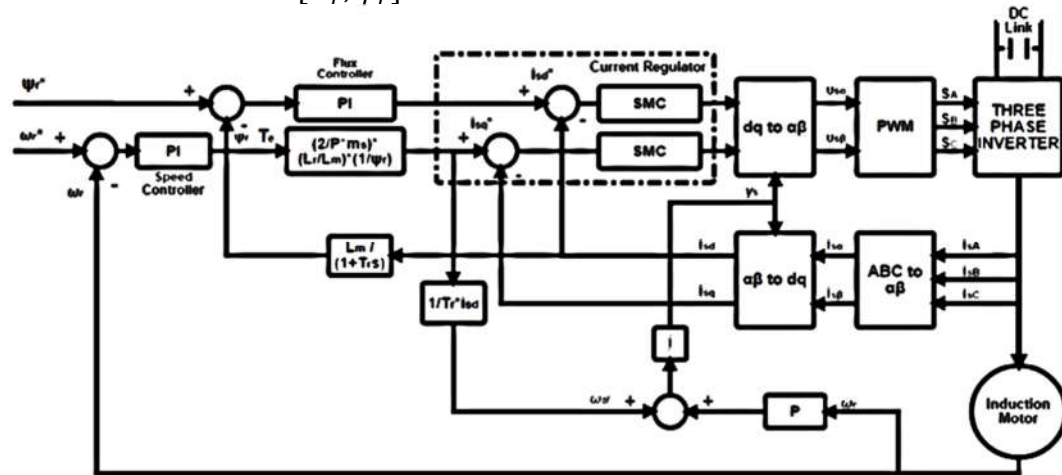


Fig. 3 Blok diagram of decoupled indirect field oriented control scheme for model based controller

7. IFOC – SLIDING MODE CONTROL DESIGN IN CURRENT REGULATOR

The sliding surface is presented by [16] and [17] :

$$S(e; t) = \left(\frac{d}{dt} + \lambda \right)^{n-1} e$$

where n is degree of sliding surface; $e = x_{desire} - x$ is error and λ is constant.

The strategies to design sliding mode control is as follows :

$$U_{smc} = U_{eq} + U_n \tag{11}$$

Lyapunov function used to guarantee the system stability is :

$$V = 1/2 S^2$$

this lyapunov function has derivative :

$$\dot{V} = S\dot{S}$$

with :

$$S = \lambda e$$

$$\dot{S} = \lambda \dot{e}$$

From equation 10, 11 and Lyapunov stability function, the current regulator controller is :

$$U_{eq} = B^{-1} (\dot{X}_{desire} - AX - C\psi_r) \tag{12}$$

with :

$$B^{-1} = \begin{bmatrix} \sigma L_s & 0 \\ 0 & \sigma L_s \end{bmatrix}$$

where B^{-1} is the inverse of matrix B; \dot{X}_{desire} is the differential desire state vector of current regulator state space.

$$U_n = kS + \beta \text{sign}[S] \quad (13)$$

By substituting equation 12 and equation 13 to equation 11, the sliding mode control design is :

$$U_{smc} = B^{-1} (\dot{X}_{desire} - AX - C\psi_r) + kS + \beta \text{sign}[S]$$

The stator current regulator in D-axis is :

$$U_{smc}(U_{sd}) = \sigma L_s \left(\dot{i}_{sd\ desire} + \frac{R_{sm}}{\sigma L_s} i_{sd} - \omega_s i_{sq} - \frac{L_m}{L_r T_r} \psi_r \right) + k[S] + \beta \text{sign}[S]$$

The stator current regulator in Q-axis is :

$$U_{smc}(U_{sq}) = \sigma L_s \left(\dot{i}_{sq\ desire} + \frac{R_{sm}}{\sigma L_s} i_{sq} - \omega_s i_{sd} - \frac{L_m \omega_{sl}}{L_r} \psi_r \right) + k[S] + \beta \text{sign}[S]$$

8. RESULT AND DISCUSSION

The proposed model based controller in current regulator side of IFOC for robustness and stability controller using SMC is compared with PI controller in variable rotor speed and stator current in DQ rotating frame that shown in Figure 3. By making the same controller and its parameter in speed and flux controller the performance of a model based controller can be compared with PI controller in a current regulator. The parameter controller of current regulator is shown in Table 1. In transient response of 900 rpm of rotor speed shown in Figure 4, the PI controller has 62.17 ms of rising time, 1.97 ms of undershoot and 0.5 % overshoot. The SMC has 6.76 ms rise time and 0.5 % overshoot. In achieving a reference speed SMC, gives a better response than PI controller with rising time less than 8 ms shown in Table 2 and 3. The performance of SMC and PI controller in overshoot and undershoot side are nearly same.

Table 1. Controller parameter of current regulator

Current Regulator	Controller Parameter				
	PI		SMC		
	Kp	Ki	λ	k	β
i_{sd}	10	0.2	25	10	15
i_{sq}	10	0.2	25	10	15

The robustness and stability of model-based controller using SMC to overcome the disturbance is shown in Figure 4 with 1.5 Nm of torque load (t_o). In SMC, the speed response in overcoming the disturbance is decreasing but less than 2 % of steady state error in reference speed 900 rpm. The robust model-based controller in multiloop IFOC system designed in current regulator using First Order Sliding Mode Control (FOSMC) that contains chattering phenomenon in Figure 5. The comparison between model-based and PI controller proven that model-based controller such as SMC is better in overcoming the disturbance like in Figure 6.

In Figure 7, the rotor speed response of IFOC method which uses PI controller and SMC is compared in variable reference speed and torque load. Controller parameter which uses these results are shown in Table 4. The results show that SMC controller can compensate the disturbance but not the PI controller. When the rotor speed is under 1.5 Nm disturbance at 0.5 seconds, SMC controller can compensate the disturbance (robust) but not for PI controller. When the reference speed is changed in to be 1.150 rpm and is under disturbance, the SMC controller shows the robustness but PI controller is not. The PI controller reaches the reference speed again when the torque load decrease to 1.5 seconds. This condition repeats in 2 and 2.5 ; 3 and 3.5 seconds.

Table 2. First comparison of PI controller and SMC in transient response

Reference Speed (rpm)	700		800		900	
Transient Parameter	PI	SMC	PI	SMC	PI	SMC
Rise Time (ms)	52.04	4.55	57.30	4.90	62.17	6.76
Overshoot (%)	3.65	2.58	0.5	1.53	0.5	0.5
Undershoot (ms)	1.97	8.51	1.99	1.94	1.97	1.89

Table 3. Second comparison of PI controller and SMC in transient response

Reference Speed (rpm)	1000		1100		1200	
Transient Parameter	PI	SMC	PI	SMC	PI	SMC
Rise Time (ms)	83.87	6.48	90.98	7.69	112.63	6.54
Overshoot (%)	0.5	0.5	0.5	0.5	0.5	0.5
Undershoot (ms)	1.96	2.08	1.99	1.98	1.97	2.26

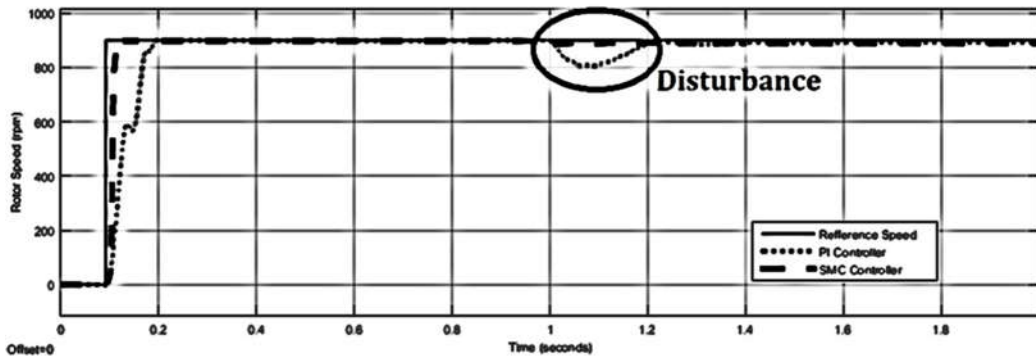


Fig. 4 IFOC's rotor speed response using PI controller and SMC under disturbance at 1 second and reference rotor speed at 900 rpm

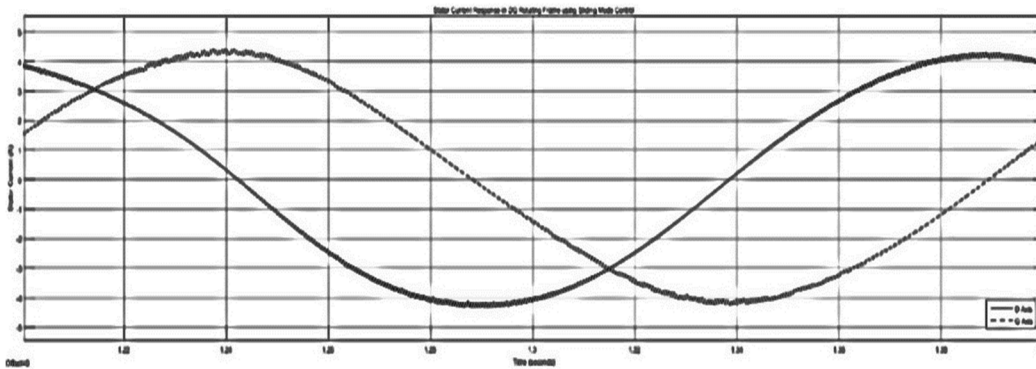


Fig. 5 Chattering effect in First Order Sliding Mode Control (FOSMC)

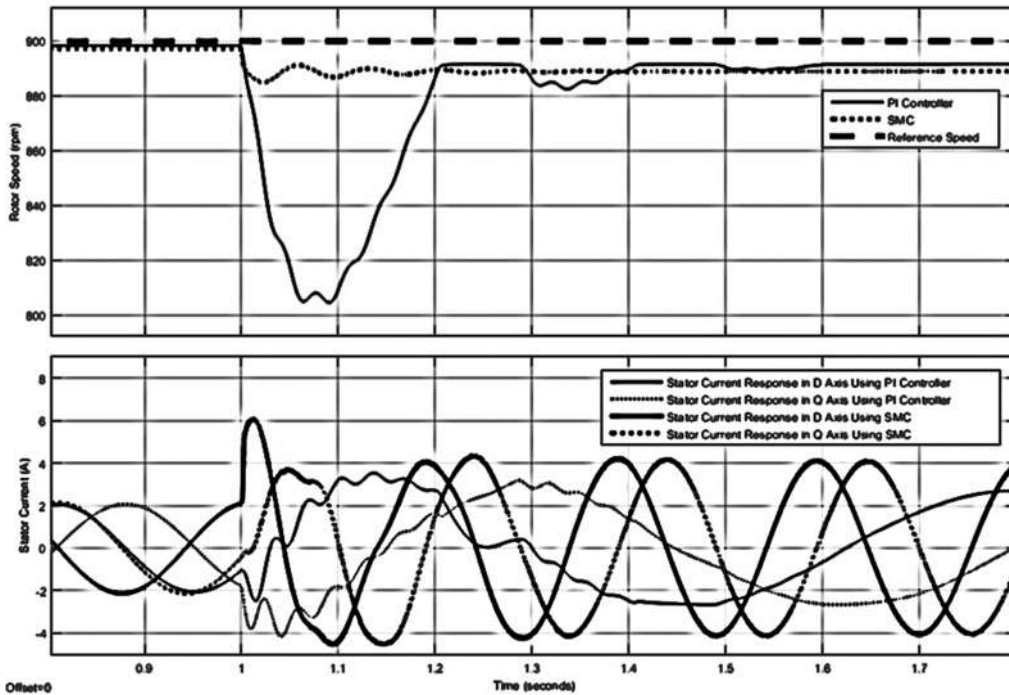


Fig. 6 The comparison between PI controller and SMC in disturbance area for rotor speed and stator current in DQ rotating frame at reference speed 900 rpm

Table 4. Controller parameter of current regulator for variable speed and torque load

Current Regulator	Controller Parameter				
	PI		SMC		
	Kp	Ki	λ	k	β
i_{sd}	14	0.1	30	10	25
i_{sq}	14	0.1	30	10	25

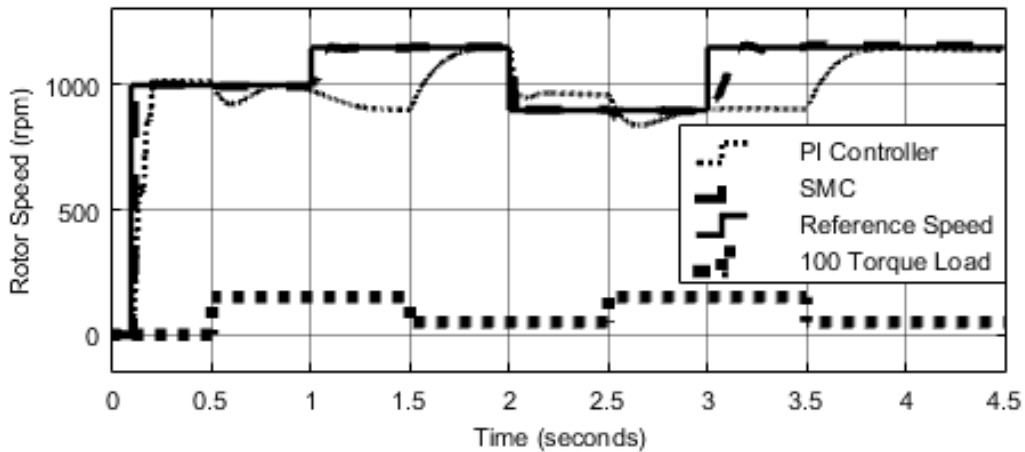


Fig. 7 The comparison between PI and SMC controller in variable reference speed and torque load

The comparison between sliding mode design in current regulator and speed controller in rotor speed side is shown in Figure 8. It shows that the robustness and stability under 0.5 Nm of torque load is achieved in rotor speed by designing the controller in current regulator or speed control. However, sliding mode control which design in speed controller has chattering phenomenon that is danger to the hardware. On another hand, sliding mode controller designed in current regulator has no chattering phenomenon which is shown in Figure 9. The comparison of stator current in DQ rotating frame shows the sliding mode in current regulator ($i_{sd} = 2.79$ A and $i_{sq} = 2.77$ A) is lower than speed control ($i_{sd} = 2.96$ A and $i_{sq} = 3.00$ A) which shown in Figure 10 and Table 5.

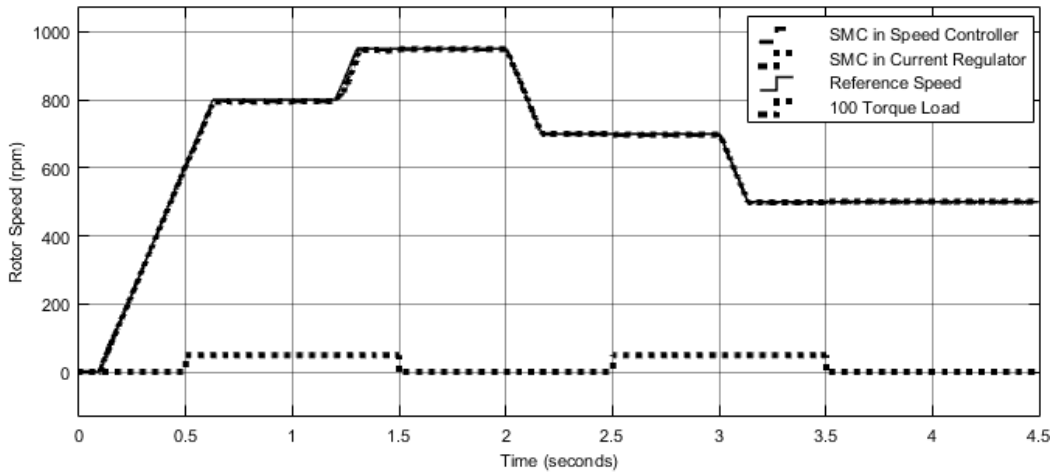


Fig. 8 Variable speed response using SMC in Speed controller and Current Regulator with various torque load

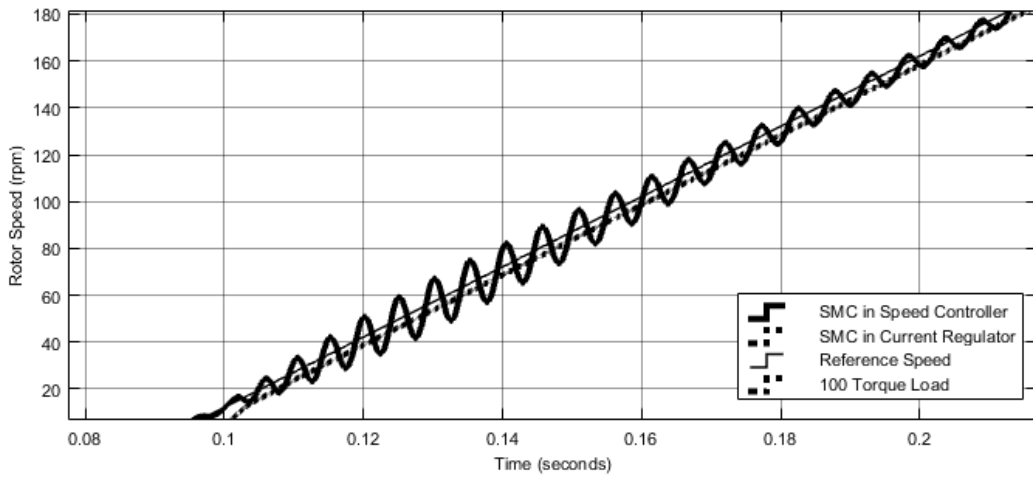
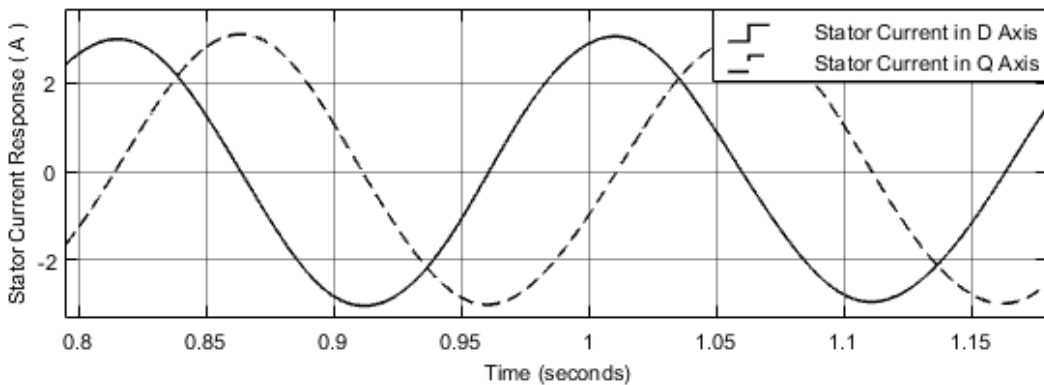
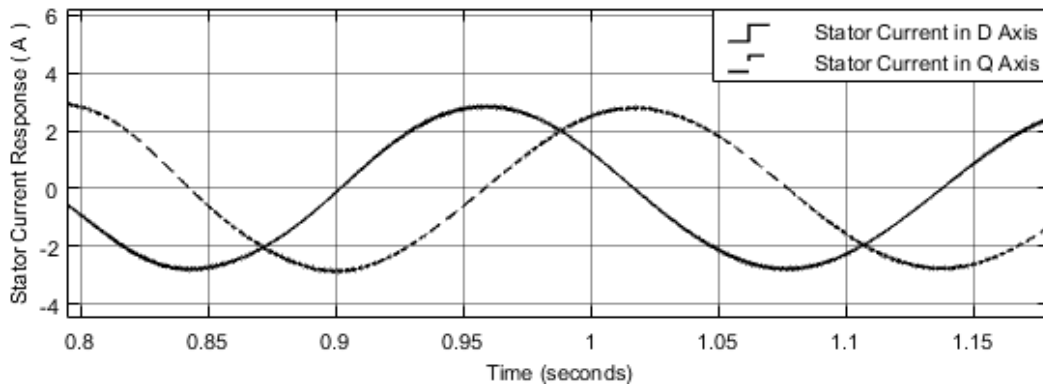


Fig. 9 Chattering phenomenon in Speed Response



(a)



(b)

Fig. 10 Stator Current Response in DQ rotating frame (a) SMC in speed controller
(b) SMC in current regulator

Table 5. Comparison table of SMC in speed controller and current regulator

	Stator Current (A)	
	In D Axis	In Q Axis
SMC in Speed Controller	2.96	3.00
SMC in Current Regulator	2.79	2.77

9. CONCLUSION

In this paper, state space equation of current regulator in Indirect Field Oriented Control (IFOC) has been proposed to design a model based controller using Sliding Mode Control (SMC). To guarantee the stability, SMC is designed by using Lyapunov stability theory. SMC has better performance in the transient response of rotor speed than PI controller with rising time less than 8 ms in various reference speed. In robustness and stability aspect SMC has better performance than PI in rotor speed and torque load. It is proven in the ability of SMC to overcome 1.5 Nm of torque load that shown in Figure 6. Figure 7 shows the robustness of SMC in variable reference speed and torque load which compare with PI controller. By designing SMC in current regulator, the chattering phenomenon which is danger to the hardware does not exist in rotor speed and the stator currents are smaller than SMC in the speed controller. The stator current in direct axis (i_{sd}) decreased by 5.74% and in quadrature axis (i_{sq}) by 7.66%.

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