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Performance Study of Sliding Mode Speed Controller for Induction Motor Vector Control Using MATLAB/SIMULINK

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Abstract- The sliding mode controller (SMC) considers an advanced controller, due to its high dynamic performance, tracking accuracy and disturbances rejection. However, the discontinuous function in the control law causes the chattering in the system's trajectories (oscillation around the desired value). This causes various unwanted effects such as current harmonics and torque ripple. Furthermore, the control gain values found in the control law can affect limiting chattering and the system response speed. Therefore, a comprehensive examination and analyse the performance of the sliding mode speed controller for a three-phase induction motor (IM) controlled by the rotor flux orientation technique in terms of improving the dynamic performance, ability to overcome disturbances and reducing the chattering problem. The designed sliding mode controller performance is verified by practical approximation of simulations using MATLAB/SIMULINK. The simulation results show that the control law gains have a more significant effect on reducing the chatter phenomenon and improving the system performance from the discontinuous function.

Keywords Sliding mode control, Field-Oriented Control, Induction motor, MATLAB/SIMULINK.

1. Introduction

Induction motors are used extensively in industrial applications and electric vehicle traction motor applications due to their simple structure, low maintenance, ruggedness, and durability [1-2].

In induction motors, torque is obtained from the nonlinear function of fluxes and currents. Asynchronous motors require complex control algorithms due to their nonlinear structure. This difficulty can be overcome with the field-oriented control (FOC) technique, where flux and currents are easily separated from each other. Thus, the speed becomes linearly controllable under certain conditions, such as in separately excited DC motors [3]. The two main classifications of FOC schemes are the direct field-oriented control (DFOC) and indirect field-oriented control (IFOC), discovered by Hasse in 1968 and Blaschke in 1972, respectively [4,5]. The DFOC method tries to measure or estimate the machine flux either by mounted flux sensors in the air gap or by sensing stator voltages; however, this technique is not considered accurate at low speeds [6]. On the other hand, IFOC is synthesized by properly controlling the slip frequency and hence provides more accuracy over a wide speed range [7]. Therefore, the indirect scheme is preferred over the direct scheme [8]. Conventional PI controllers are widely used in field-oriented control techniques [9,10]. However, high performance cannot be obtained from PI controllers when motor parameters change during operation.

In recent studies, various nonlinear control techniques such as sliding mode control have been proposed. The sliding-mode control concept emerged towards the end of the 1950s and started to spread after Utkin's study in 1977 [11].

The sliding-mode control method, also known as Variable Structure Control (VSC), is an effective control method used in the control of systems that are linear and non-linear under parameters change or disturbances effect. High-performance controllers are characterized by high dynamic performance, fast response, and high durability against changes affecting system parameters, where the sliding mode controller is a suitable control technique for induction motors.

The switching function in the control law provides a high dynamic response in the transient states and a good performance against uncertainties. However, the switching function causes chattering (oscillation around the desired value) in system trajectories, which causes various undesirable effects such as current harmonics and torque ripples. Several advanced studies have been presented to suppress the chattering phenomenon and torque ripples. The saturation function instead of the sign function and choosing the appropriate saturation region for the system was used [12-15]. In general, adding a thin boundary layer around the sliding surface can solve the chattering problem. However, the slope of the saturation function is a compromise between controller performance and chattering reduction. Also, stability in the layer cannot be guaranteed and insufficient selection of the boundary layer can result in an unstable tracking response.

Therefore, to overcome these problems, many studies used fuzzy logic control (FLC) to design a saturation or sigmoid function with a nonlinear slope within the saturation boundaries surrounding the sliding surface instead of the sign function [16–20].

However, the importance of the gain values of the control law in reducing the chatter problem and improving the dynamic performance of the system is not seriously mentioned in the literature. Therefore, this research aims firstly to design a sliding mode controller for speed control of a three-phase induction motor by FOC technique. Then examining the performance of the designed controller by presenting a study that shows the effect of the switching function and the gain values contained in the control law on limiting the chattering phenomenon and increasing the system response speed..

The main contributions of this work are as follows:

(1) The speed controller of the induction motor is designed in detail according to the sliding mode control technique.

(2) A comprehensive investigation and analysis of the performance of the sliding mode controller under the conditions of changing the control law gain value and replacing the discontinuous sign function with the continuous sigmoid function are presented.

(3) Provide comprehensive concepts about the effect of gain values on the performance of the sliding mode controller, and thus consider the presented study as a base for proposing advanced adaptive schemes based on fuzzy logic control or neural networks for self-tuning online for the control law gain values.

2. Mathematical Model of IM

The induction motor can be modelled in (d-q) synchronously rotating frame, the motor behaviour is defined by the appropriate selection of the stator currents and rotor flux as state variables, using the following equations

$$\begin{bmatrix} \frac{di_{sd}}{dt} \\ \frac{di_{sq}}{dt} \\ \frac{d\Phi_{rd}}{dt} \\ \frac{d\Phi_{rq}}{dt} \end{bmatrix} = \begin{bmatrix} -a_5 & \omega_s & a_3 & a_4\omega \\ -\omega_s & -a_5 & -a_4\omega & a_3 \\ a_2 & 0 & -a_1 & \omega_s-\omega \\ 0 & a_2 & -\omega_s+\omega & -a_1 \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ \Phi_{rd} \\ \Phi_{rq} \end{bmatrix} + \begin{bmatrix} b & 0 \\ 0 & b \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} \quad (1)$$

where:

$a_1 = \frac{R_r}{L_r}$, $a_2 = \frac{L_m R_r}{L_r}$, $a_3 = \frac{L_m R_r}{\sigma L_s L_r^2}$, $a_4 = \frac{L_m}{\sigma L_s L_r}$,

$a_5 = \frac{L_r^2 R_s + L_m^2 R_r}{\sigma L_s L_r^2}$, $b = \frac{1}{\sigma L_s}$, $\sigma = \frac{1 - L_m^2}{L_s\, L_r}$

The motion equation and the electromagnetic torque produced by the induction motor are given by the relation:

$$\frac{d\omega}{dt} = \frac{P}{J}T_{em} - \frac{P}{J}T_L - \frac{F}{J}\omega \quad (2)$$

$$T_{\text{em}} = \frac{3PL_m}{2\ L_r}\left(\Phi_{rd}\cdot i_{sq} - \Phi_{rq}\cdot i_{sd}\right) \quad (3)$$

P is the pole pair number of the motor; J is the total inertia of the system and F is the viscous friction coefficient. R_s and R_r are the stator and rotor winding resistances; L_s, L_r and L_m are the stator, rotor and mutual inductances. σ is the total leakage factor. The load torque T_L is considered an external disturbance. The angular synchronous speed is given by: $\omega_s = \omega + \omega_{sl}$ where: ω and ω_{sl} are the rotor and slip angular speed.

3. Field Oriented Control

The principle of FOC consists of aligning the d axis of the revolving reference frame with the rotor flux vector Φ_r, as illustrated in Fig.1.

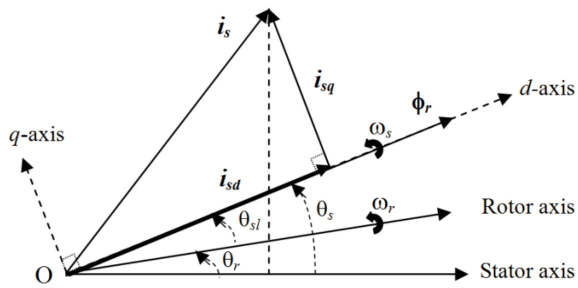

Fig.1. Phasor diagram explaining indirect field-oriented control

Thus, the orientation condition of the rotor flux is ϕ_{rq}=0, $\phi_{rd} = \phi_r$, and the mathematical model of the induction motor can be expressed using the following equations according to this condition:

$$\frac{di_{sd}}{dt} = -a_5\, i_{sd} + \omega_s\, i_{sq} + a_3\, \phi_r + b\, V_{sd} \tag{4}$$

$$\frac{di_{sq}}{dt} = -\omega_s\, i_{sd} - a_5\, i_{sq} - a_4\, \omega\, \phi_r + b\, V_{sq} \tag{5}$$

$$\frac{d\Phi_r}{dt} = a_2\, i_{sd} - a_1 \phi_r \tag{6}$$

$$0 = a_2\, i_{sq} - \omega_r\, \phi_r \tag{7}$$

$$T_{em} = \frac{3}{2}\frac{PL_m}{L_r}\, \Phi_{rd}\, i_{sq} = K_t\, i_{sq} \tag{8}$$

In order to guarantee a correct alignment of the revolving reference frame, the flux angular position θ_s is obtained to perform the direct and inverse Park transformations as follows:

$$\theta_s = \int \omega_s\, dt = \int (\omega + \omega_{sl})\, dt \tag{9}$$

The slip angular speed can be calculated by the following equation:

$$\omega_{sl} = \frac{a_2\, i_{sq}}{\Phi_{rd}} = \frac{a_1\, i_{sq}}{i_{sd}} \tag{10}$$

Fig. 2 shows the block diagram of the FOC algorithm using the studied sliding mode speed controller.

The currents measured from the three-phase system are converted to the binary stationary reference frame system with the Clarke transform and then converted to the synchronous reference frame with the Park transform. The resulting dq axis currents are used as the feedback of the inner loops. The reference voltage values obtained from the current controllers form the magnitudes of the reference voltage signals for the PWM unit with the reverse Park and Clarke transform. The signals received from the PWM unit form the trigger pulses for the IGBT switches in the inverter.

To get the rotor flux vector oriented to the d-axis, the steering angle θ_s must be obtained. The motor speed is measured and used as the feedback of the SMC controller.

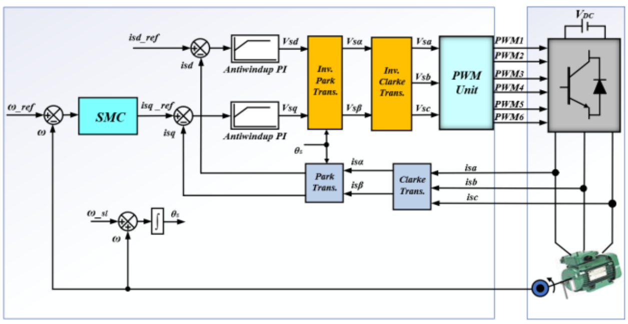

Fig.2. Block diagram of the FOC algorithm using the studied sliding mode speed controller

4. Sliding Mode Control

The basic principle of sliding-mode control requires an ideal control law to produce changes in the system state trajectory on phase planes. The purpose is to control the system trajectory to move along or toward the sliding surface. When the state trajectory reaches the sliding surface, a switching control law is employed to ensure that the system trajectory remains on the sliding surface [21]. Finally, the trajectory slides to the origin along the sliding surface, similar to shown in Fig. 3.

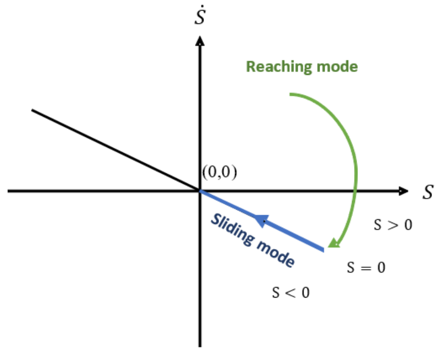

Fig.3. The reaching and sliding modes for a second-order system

The design of SMC can be achieved in two successive steps:

First step: determination of sliding surface

The sliding surface is generally defined by:

$$S(t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} (x_{ref} - x) \tag{11}$$

where: x presents the state vector, x_{ref} indicates the reference state vector, n is the degree of the sliding mode and λ is a constant and $\lambda > 0$. A larger λ can give a faster response. However, great a value of λ could lead to undesired overshoots.

Second step: Control law design

The sliding mode control law has two components and can be expressed as follows:

$$u(t) = u_{eq}(t) + u_{sw}(t) \tag{12}$$

The component u_{eq} called equivalent control is obtained by setting the surface derivative to zero $\dot{S}(t) = 0$, its role being to maintain the system on the sliding surface which is defined by $S(t) = 0$. The other constituent u_{sw} is the discontinuous control (switching control) which ensures the convergence of system state trajectory toward the sliding surface. The reaching condition is based on Lyapunov theory stability and must verify $S.\dot{S} < 0$.

5. Design of Sliding Mode Speed Controller

Derive a sliding-mode speed controller can be started from the mechanical equation of an induction motor as follows:

$$T_{em} - T_L = J\,\frac{d\omega}{dt} + F\omega \;\Rightarrow\; \frac{d\omega}{dt} = \frac{1}{J}T_{em} - \frac{F}{J}\omega - \frac{1}{J}T_L \tag{13}$$

$$T_{em} = \frac{3}{2}\frac{PL_m}{L_r}\, \Phi_{rd}\, i_{sq}^{*} = K\, i_{sq}^{*} \tag{14}$$

where i_{sq}^* is the torque current command.

Derivative of the Equation (13):

$$\ddot{\omega} = \frac{1}{J}\dot{T_{em}} - \frac{F}{J}\dot{\omega} \quad (15)$$

Speed error and its first and second derivative are defined as follows:

$$e = \omega^* - \omega \quad (16)$$

$$\dot{e} = -\dot{\omega} \quad (17)$$

$$\ddot{e} = -\ddot{\omega} = -\frac{1}{J}\dot{T_{em}} - \frac{F}{J}\dot{e} = -\frac{1}{J}K\,u_{eq} - \frac{F}{J}\dot{e} \quad (18)$$

Where: $u_{eq} = \frac{di_{sq}^*}{dt}$ and ω^* is a rotor speed reference.

The Equations (17) and (18) can be represented using a state equation:

$$\begin{bmatrix} \dot{e} \\ \ddot{e} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{F}{J} \end{bmatrix} \begin{bmatrix} e \\ \dot{e} \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{K}{J} \end{bmatrix} u_{eq} \quad (19)$$

Using the sliding surface that given in equation (11), for *n*= 2

$$S = \dot{e} + \lambda e \quad (20)$$

For obtaining the equivalent control $\dot{S}(t) = 0$

$$\dot{S} = \ddot{e} + \lambda\dot{e} \quad (21)$$

$$\dot{S} = -\frac{1}{J}K\,u_{eq} - \frac{F}{J}\dot{e} + \lambda\dot{e} = 0 \quad (22)$$

Then the equivalent control u_{eq} can be expressed as follows:

$$u_{eq} = \frac{1}{K}(J\lambda - F)\dot{e} \quad (23)$$

Equation (23) shows the dynamic behaviour of the system on the sliding surface. For the state variable to reach the sliding surface, an appropriate discontinuous control law must be used as shown in the following equation:

$$u_{sw} = Q\,sign(S) + KS \qquad Q, K > 0 \quad (24)$$

where

Q: Switching gain and $sign(S) = \frac{(S)}{|(S)|} = \begin{cases} 1 & if \quad S > 0 \\ 0 & if \quad S = 0 \\ -1 & if \quad S < 0 \end{cases}$

The total control equation will be as follows:

$$u = \frac{1}{K}(J\lambda - F)\dot{e} + Q\,sign(S) + KS \quad (25)$$

Lyapunov stability theory was used to ensure the stability of the sliding-mode controller. The Lyapunov function is defined as:

$$V = \frac{1}{2}S^2 \quad (26)$$

The system's stability condition is $\dot{V} < 0$. The derivative of Equation (26) is

$$\dot{V} = S\,\dot{S} \quad (27)$$

Equation (28) is obtained from Equations (22) and (25) as follows:

$$\dot{S} = -\frac{Q}{J}sign(S) - \left(\frac{K}{J}\right)S \quad (28)$$

$$S\,\dot{S} = -S\left(\frac{Q}{J}\right)sign(S) - \left(\frac{K}{J}\right)S^2 =$$

$$= -\left(\frac{Q}{J}\right)|S| - \left(\frac{K}{J}\right)S^2 < 0 \quad (29)$$

Equation (29) shows that Q and K must be positive constants to satisfy $\dot{V} < 0$ and ensure successful sliding-mode control.

the time required to reach the sliding mode surface can be derived as

$$\left|\int_0^t \dot{S}\,dt\right| = \left|\int_0^t -\left(\frac{Q}{J}\right) - \left(\frac{K}{J}\right)\,dt\right| \quad (30)$$

Based on (13) and (17), the required time can be derived as

$$t = \frac{J\,|S(t) - S(0)\,|}{Q+K} \quad (31)$$

It is evident that $S(t)$ = 0 based on the sliding mode theory, and thus last equation can be rewritten as follows:

$$t = \frac{J\,|S(0)\,|}{Q+K} \quad (32)$$

It is noted that the reaching time can be regulated directly by the gains *Q* and *K*. If gains are designed larger, the reaching speed will be faster.

6. The Performance Study of Designed Sliding Mode Controller

The sliding mode controller has high dynamic performance, fast response and high impedance to changes affecting system parameters. But the main problem is the chattering phenomenon resulting from the discontinuous control law. To study the performance of the sliding mode controller and to limit the chattering phenomenon, the discontinuous control law included in Equation (24) will be studied in two cases:

A. Case 1:

The alternate control law to reduce chattering phenomena is used by applying smooth approximation by replacing the sign function with the sigmoid function as:

$$\text{Smooth}(S) = \left[\frac{(S)}{|(S)| + \beta}\right] \quad (33)$$

Where β: small positive value.

Fig. 4 shows a representation of the function shown by Equation (33) in Matlab at variable values of the constant β.

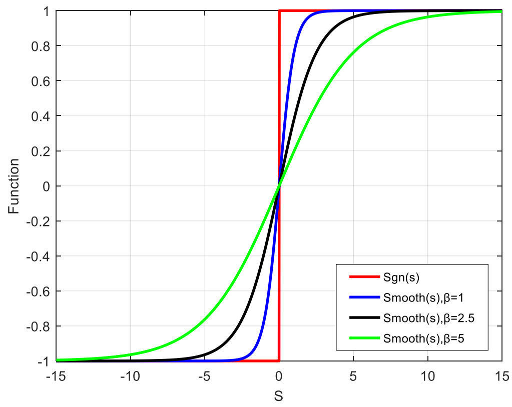

Fig.4. The smooth function by variable values of the constant β.

B. Case 2:

The experimental control coefficients Q and K present in the switching control law are of great importance to reduce the chattering phenomenon, but the second term of the switching control law Equation (24), which includes the coefficient K that has a large value in the transient states and a small value in the steady-state, because it contains the sliding function (S), which must equal to zero on the sliding surface. Therefore, Q switching gain has the greatest impact on the performance of the system in both transient and steady conditions and reduces the chattering phenomenon.

Thus, the equation expressing the discontinuous control law at variable values of switching gain is given as follows:

$$u_{sw} = \tilde{Q}\ sign(S) + KS \qquad (34)$$

7. Simulation Results and Discussion

The validity and effectiveness of the proposed scheme were verified by Matlab/Simulink. Fig. 5 shows the system's overall simulation model using Matlab/Simulink. For simulation, the (Runge-Kutta) method is used to solve differential equations. The sampling time is $Ts = 20\mu s$ and the converter switching frequency was set as $5KHz$. The nominal parameters of the IM are given in Table 1.

Table 1. Induction Motor Nominal Parameters

P_n=1 KW	P=2 pairs	U_n=380 V	f_n=50 Hz
R_s=7.2 Ω	L_s=0.28 H	R_r=1.35 Ω	L_r=0.075 H
L_m=0.118 H	T_L=6 N.m	J=0.006 kg/m^2	F=0.0046 N.m.s

Where the simulation results are presented according to the previous cases mentioned.

For case 1: The system performance is compared in terms of the chattering phenomenon and response speed when using both the sign function and the sigmoid function under various operating conditions. Positive and negative variable reference speed and also the nominal load disturbance torque suddenly is applied at t = 0.75s and removed at t=3.5s.

Fig. 6 shows the discontinuous control signal for both the traditional sign and the smooth function. It is observed that the Sigmoid function provides more smoothness and eliminates the momentary change between the two values [-1, 1] as in the sign function.

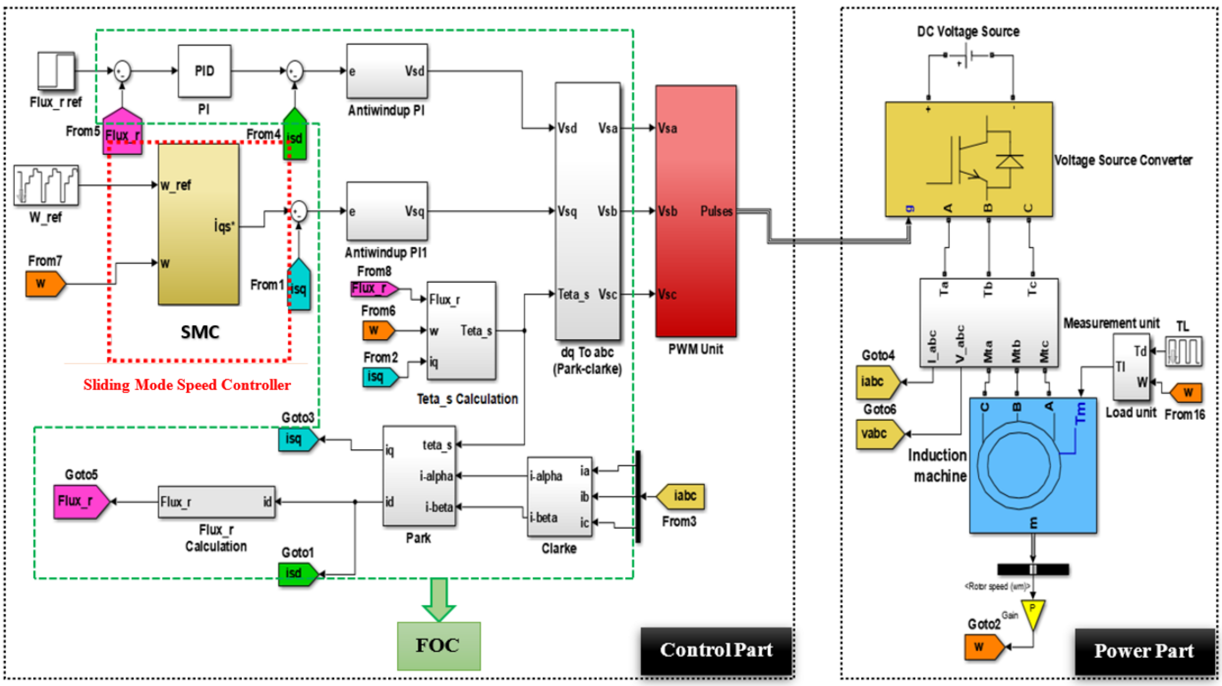

Fig.5. Overall simulation model.

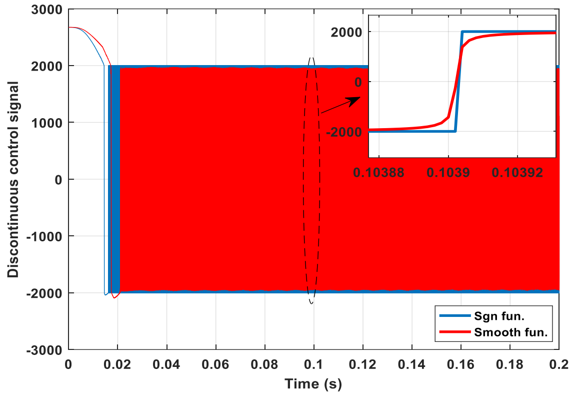

Fig.6. Discontinuous control signal.

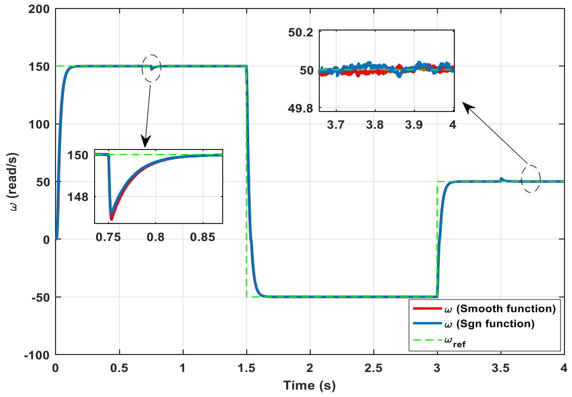

Fig.7. Speed response at case-1.

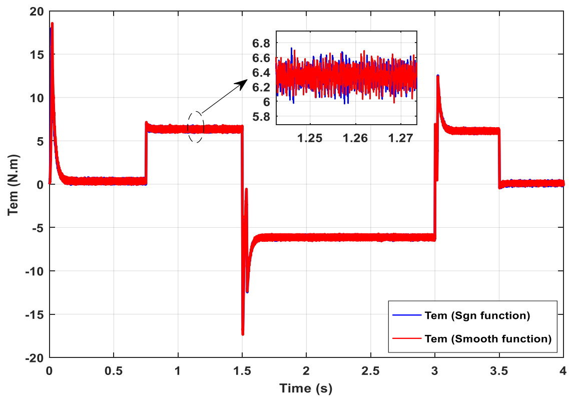

Fig.8. Electromagnetic torque response at case-1

Fig. 7 shows the speed response by using both two functions. Firstly, generally, it can be seen that the sliding mode controller provided high dynamic performance in the transient and steady states and under different operating conditions. Secondly, it can be said that the performance of the sliding mode controller for both two functions is similar, as it is noticed the chattering reduction and response speed when using the smooth function in the discontinuous control law.

This is also shown in Fig. 8, where a very slight chattering reduction in the electromagnetic torque response when using the smooth function is observed.

For case 2: The system performance is compared in terms of the chattering phenomenon and response speed when applying variable values of switching gain Q under various operating conditions. Positive and negative variable reference speed and also the nominal load disturbance torque suddenly is applied at t = 0.75s and removed at t=3.5s. The values of the gains included in the discontinuous control law are chosen as follows: Q_1=5000, Q_2=500, Q_3=100, K=0.1.

Fig. 9 shows the speed response at the chosen values of the switching gain Q. The large chattering of the rotor speed is observed when a large value is chosen, while the response speed is high during transient states, and conversely, for small values, the chattering phenomenon is significantly reduced, but the response speed is small during transient states. From Fig. 10, it can be seen the big difference in the occurring chattering in the electromagnetic moment response for the different values of switching gain Q, and this is also shown in Fig. 11, which shows the stator current of phase A, where it can be noticed a significant distortion at large values of switch gain Q.

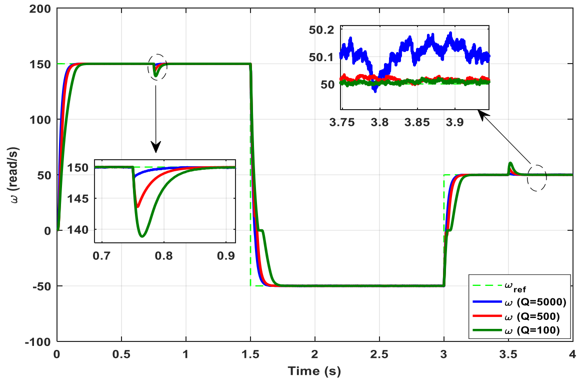

Fig.9. Speed response at case-2

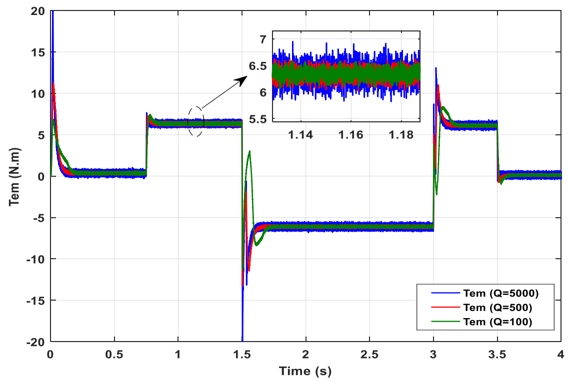

Fig. 10. Electromagnetic torque response at case-2

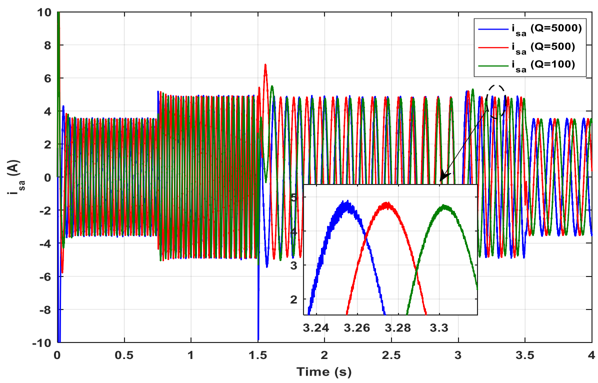

Fig. 11. Stator current of phase A at case-2

To confirm the obtained results for the proposed study, a state variable trajectory has been shown in the phase plane for the three values of Q as given in Fig. 12.

Where it is noticed, the high reaching speed of the state variable to the sliding surface (High response speed) and the large oscillation around the sliding surface (High chattering) when chosen large values of Q, but with the small values, the state variable takes more time to reach to the sliding surface with less oscillation around the sliding surface.

After presenting the detailed simulation results indicating the effect of both switching function and switching gain of discontinuous control law on sliding mode controller performance, some indicators are mentioned in Table 2, where a brief comparison for both cases studied is presented.

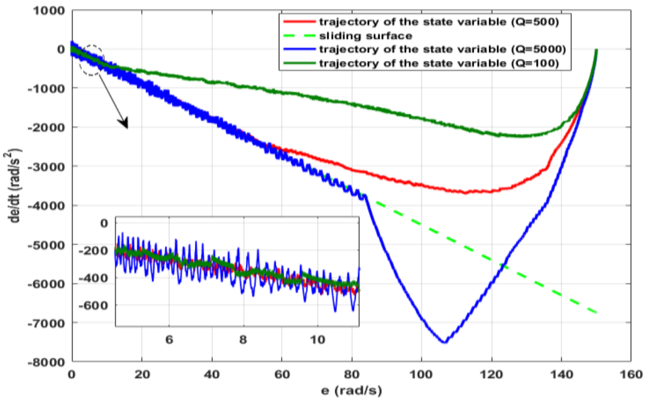

Fig. 12. Phase plane trajectories at case-2

Table 2. Performance Indicators

Indicator	Case 1: Discontinuous control function		Case 2: Discontinuous control gain	
	Sign function	Smooth function	Large value	Small value
Response speed	-	-	High	Low
Limit chattering	-	Poor	-	High

Finally, the SMC performance with the traditional PI controller is compared in terms of the chattering phenomenon and response speed when applying variable values of switching gain Q under various operating conditions. Positive and negative variable reference speed and also the nominal load disturbance torque suddenly is applied at t = 0.75s and removed at t=3.5s. The values of the gains included in the discontinuous control law are chosen as follows: Q_1=10000, Q_2=50, K=0.1. Also, the gain values of the PI controllers are adjusted as: $K_{p\_id} = K_{p\_iq}$=500, $K_{I\_id} = K_{I\_iq}$=5000, K_{p_w}=4, K_{I_w}=100.

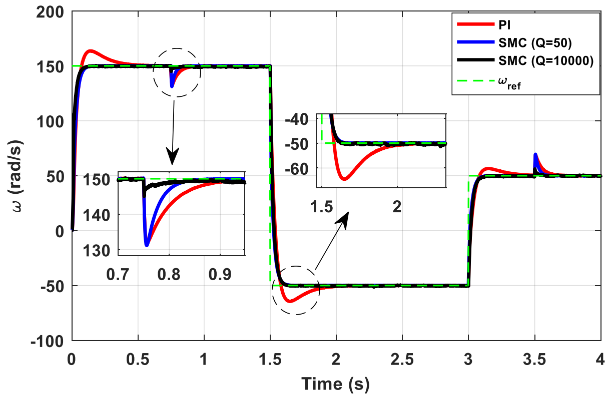

Fig.13. Speed response of the SMC and PI controller.

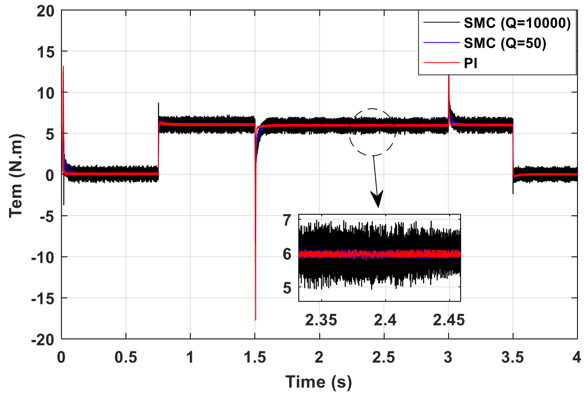

Fig. 14. Electromagnetic torque response of the SMC and PI controller.

Fig. 13 shows the speed response of the SMC and PI controller. The superiority of SMC can be observed in both cases compared with the PI controller. Where it can be noticed the overshoot in speed response with the low dynamic performance of the PI controller. On the other hand, as is observed in the previous results, when a large gain value is chosen the dynamic response in transient states and ability to overcome disturbances significantly increases. However, simultaneously, the chattering seriously increases in electromagnetic torque response, as shown in Fig. 14.

8. Conclusion

In this paper, the performance of the sliding mode speed controller for a three-phase induction motor (IM) controlled by the technique of rotor flux orientation has been studied. Two cases were studied to improve the performance of the sliding mode controller, where the effect of switching function and switching gain of discontinuous control law on system performance was studied. The detailed simulation results were presented by practical approximation of the simulations using MATLAB/SIMULINK. The results indicated that the switching gain value has a great effect on the performance of the sliding mode controller, that large values lead to increased response speed, but the chattering in the steady-state is large, while small values lead to decrease response speed, but the chattering in the steady-state is small. from the obtained study results, future studies can be proposed to design an adaptive sliding mode controller based on fuzzy logic approach or neural networks to tune gain value for obtaining optimal performance of the sliding mode controller.

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