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Speed Controller of Three Phase Induction Motor Using Sliding Mode Controller

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ABSTRACT

In this paper, an adaptive integral Sliding Mode Control (SMC) is employed to control the speed of Three-Phase Induction Motor. The strategy used is the field oriented control as ac drive system. The SMC is used to estimate the frequency that required to generates three phase voltage of Space Vector Pulse Width Modulation (SVPWM) invertor . When the SMC is used with current controller, the quadratic component of stator current is estimated by the controller. Instead of using current controller, this paper proposed estimating the frequency of stator voltage since that the slip speed is function of the quadratic current . The simulation results of using the SMC showed that a good dynamic response can be obtained under load disturbances as compared with the classical PI controller, The complete mathematical model of the system is described and simulated in MATLAB/SIMULINK.

Key Words: Induction Motor , Sliding Mode Control, Space vector pulse width modulation (SVPWM) , and Field oriented control.

التحكم في سرعة محرك حثي ثلاثي الاطوار باستخدام المتحكم المسيطر على سرعة الانزلاق

الخلاصة

في هذا البحث ، تم اقتراح نظام تحكم في الوضع المنزلق (SMC) مع سطح منزلق متكامل من أجل التحكم في سرعة محرك حثي ثلاثي الاطوار. يستخدم تصميم النظام نظرية التحكم الموجه (FOC) للمحركات الحثية .Induction Motor

في هذا البحث يقوم المسيطر المستعمل بتخمين التردد المطلوب لتوليد فولتية ثلاثية الاطوار لازمة لعمل العاكس (invertor) , يتم محاكاة وحدة التحكم في الوضع المنزلق في ظروف متنوعة ، وقد تم مقارنة النتائج مع مسيطر سرعة من نوع اخر و هو المسيطر PI التقليدي.

أظهرت النتائج أن التحكم في الوضع المنزلق (SMC) يمكن أن يعطي أداءً قويًا وعاليًا في ظل تغيير الحمل الخارجي ، بالمقارنة مع المسيطر التقليدي (PI controller)

الكلمات الرئيسية : محرك حثي ، نظام تحكم في الوضع المنزلق (**SMC**)، عاكس (**SVPWM**) ، نظام التحكم الموجه (**FOC**) .

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1. INTRODUCTION

The three phase Induction Motors (IM) have been earned a great interest in the recent years and used widely in industrial applications such as machine tools, steel mills and paper machines due to their low cost, high torque to size ratio, reliability, versatility, ruggedness, high durability, and the ability to work in various environments. Some control techniques have been improved to regulate these IM servo drives in high-performance applications. **Barambones, et al., 2007**, The Field-Oriented Control (FOC) method is one of the most popular techniques. Nowadays, the FOC strategy is the most common method since it ensures the decoupling of the motor torque and flux this property of FOC give an assurance that the induction motor can be controlled linearly as a separately exited DC motor. **Barambones, et al., 2007, Patakor, et al., 2011, and Hashim, et al., 2011.**

Conventional speed control of IM drives with a restricted gain such as PI controllers did Not provide an acceptable response for tracking the required trajectory. In order to overcome the parameter variation and/or load changes obstacles, the variable structure control strategy use the SMC for control the ac drive because the SMC provide many advantages, such as: good performance, robustness to the variations of the parameters or load disturbances, fast dynamic response, and simple implementation.

The SMC design require two steps: The first step of this design is selecting the suitable sliding surface *S(t) in* terms of tracking error and the second step is designing control signal of the system u*(t). Two* types of the sliding surface can be recognized in the sliding mode control, the conventional sliding surface and integral sliding surface. In this paper an integral sliding surface is presented and its interpretation is compared with that of classical PI controller.

2. MATHEMATICAL MODEL OF THE THREE PHASE INDUCTION MOTOR :

The equivalent circuit of IM in the stationary d-q reference frame is shown in **Fig.1**. The dynamic model of the IM is given by **Mikhael, et al., 2016.**

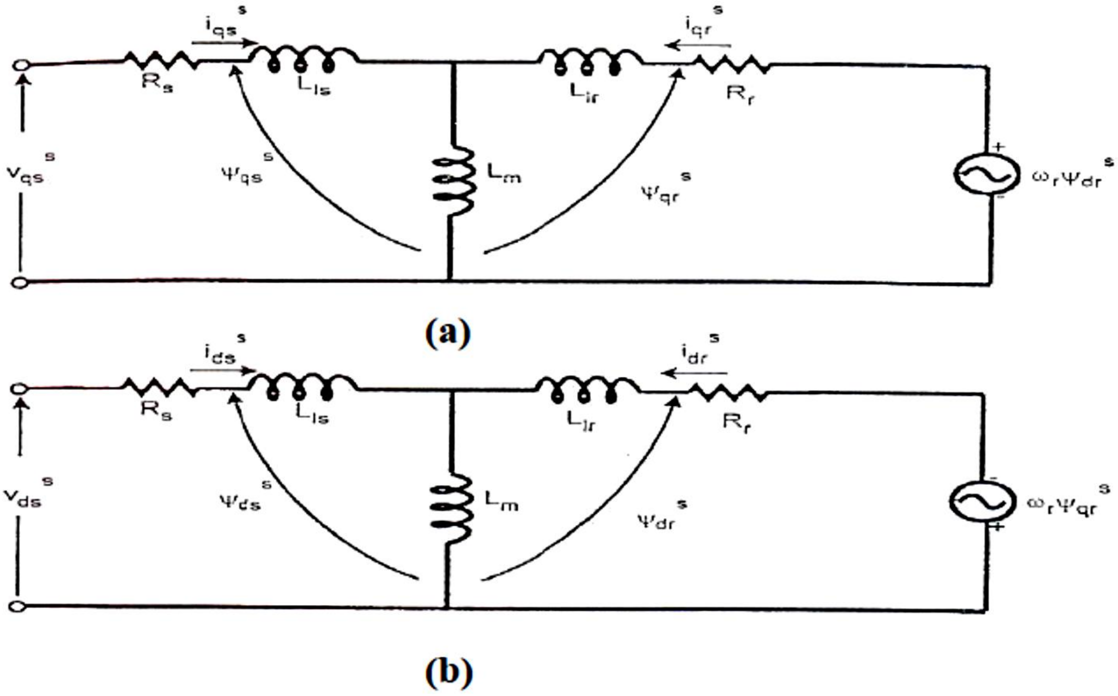

Figure 1. Induction motor equivalent circuit a) qs Circuit and b) ds Circuit.

$$v_{ds} = R_S\, i_{ds} + \frac{d}{dt}\, \Psi_{ds} \qquad (1)$$

$$v_{qs} = R_S\, i_{qs} + \frac{d}{dt} \Psi_{qs} \qquad (2)$$

$$v_{dr} = 0 = R_r\, i_{qr} + \frac{d}{dt}\ \Psi_{q_r} - \ \omega_r\, \Psi_{dr} \qquad (3)$$

$$v_{qr} = 0 = R_r\, i_{dr} + \frac{d}{dt}\, \Psi\, d_r - \ \omega_r\, \Psi_{qr} \qquad (4)$$

Where v_{ds}, v_{qs} is assign to voltage applied to the stator , i_{ds}, i_{qs} i_{dr}, i_{qr} are the stator and the rotor current , R_s, R_r are the stator and rotor resistance . $\Psi_{ds}, \Psi_{dr}, \Psi_{qs}, \Psi_{qr}$ are the rotor flux component and ω_r is angular speed of the motor , The stator and rotor fluxes are computed in d-q equivalent circuit with equations :

$$\Psi_{dr} = L_m i_{ds} + L_r i_{dr} \qquad (5)$$

$$\Psi_{qr} = L_m i_{qs} + L_r i_{qr} \qquad (6)$$

$$\Psi_{ds} = L_m i_{dr} + L_s i_{ds} \qquad (7)$$

$$\Psi_{qs} = L_m i_{qr} + L_s i_{qs} \qquad (8)$$

Where L_m *and* L_r are the Mutual inductance and the rotor inductance respectively and L_s is the stator inductance **Barambones, et al., 2007**

The equation of electromagnetic torque is given by:

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)\left(\frac{L_m}{L_r}\right)\left(\Psi_{dr} i_{qs} - \Psi_{qr} i_{ds}\right) \qquad (9)$$

Where p is referred to the number of pole of the motor. The mechanical dynamic equation which relate the motor characteristic speed ω_r to the torque is:

$$T_e - T_L = \left(\frac{2}{P}\right) J \frac{d\omega_r}{dt} \qquad (10)$$

Where T_L , J is refer to the load torque and the moment of inertia respectively , ω_{sl} is refer to the slip frequency and $\omega_r = \left(\frac{p}{2}\right)\, \omega_m$ and it can be obtained as :

$$\omega_{sl} = \frac{L_m\, R_r\, i_{qs}}{\Psi_{dr}\, L_r} \qquad (11)$$

Then the dynamic model of the IM can be expressed in **Fig. 2**.

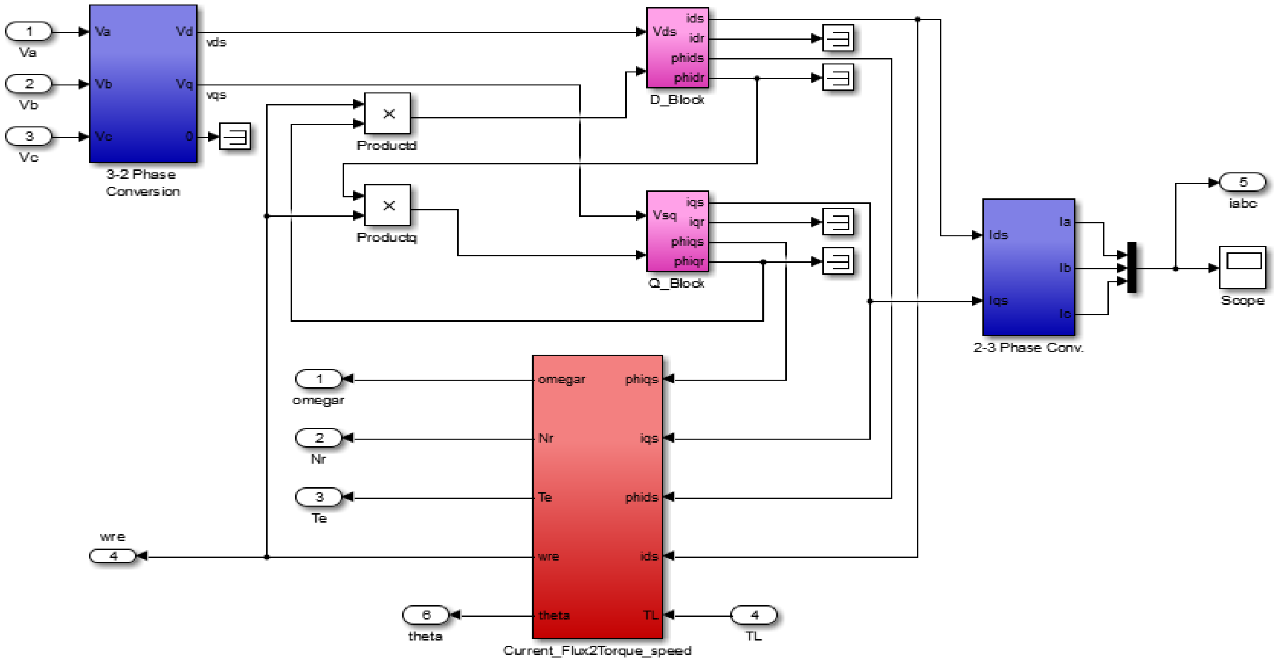

Figure 2. a: Dynamic model of IM.

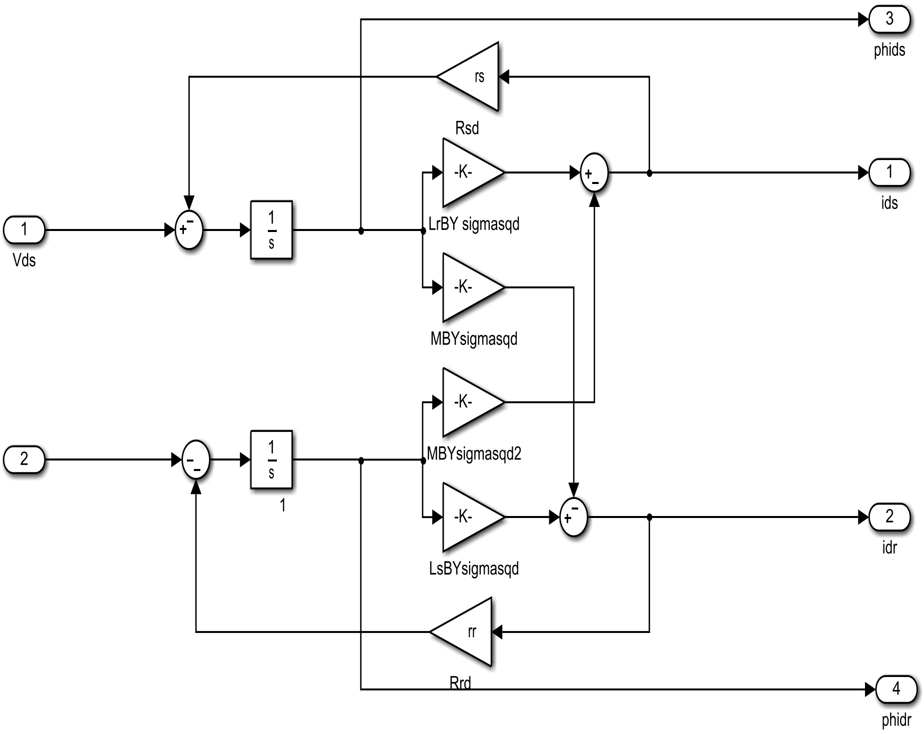

Figure 2. b: Dynamic model of IM, d _block

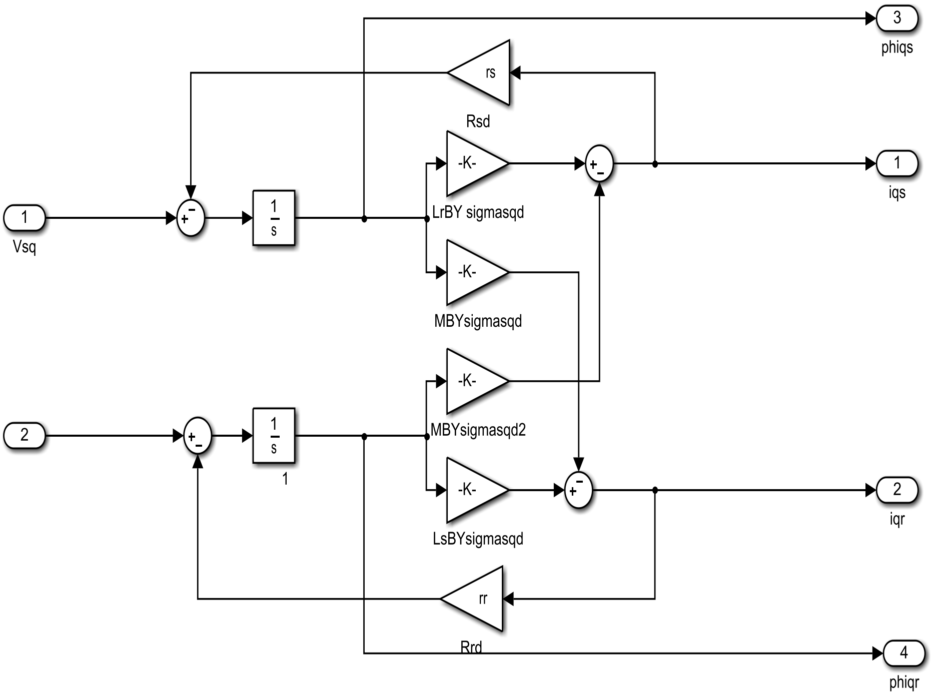

Figure 2 . c : Dynamic model of IM , q _block.

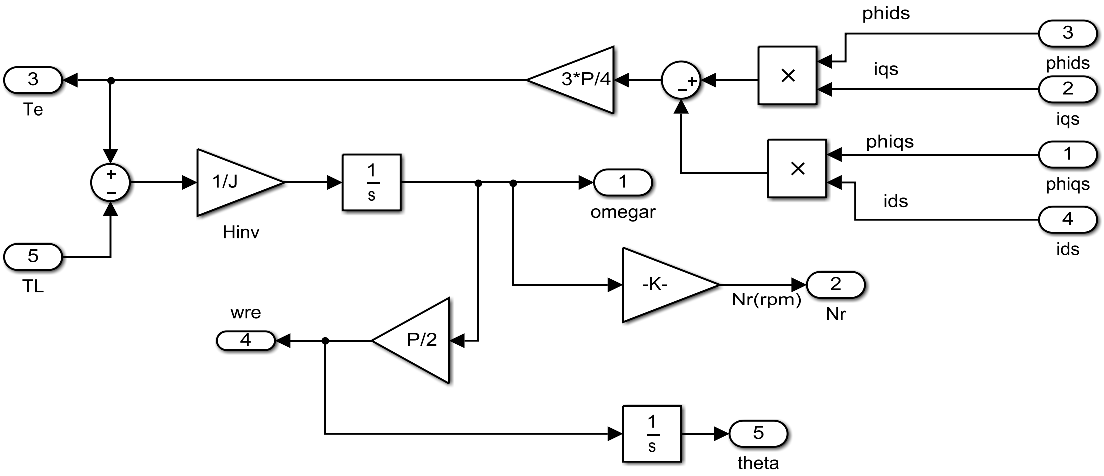

Figure 2.d. Dynamic model of IM , the mechanical dynamic equation **.**

3. SVPWM INVERTER:

This inverter consists of three legs with 6 controlled swithches (S_1 to S_6). The idea is generation of vector with amplitude V_{ref} move with angle (α) across 6 sectors shown in **Fig.3** . The SVPWM can be performed in three steps :

- Step 1. Calculation of Vref , and angle (α) from V_d and V_q
- Step 2. Calculation of the time duration T_1, T_2 , T_0
- Step 3. Calculation the switching time of every switching device (S_1 to S_6) . **JIN-WOO , 2005 .**

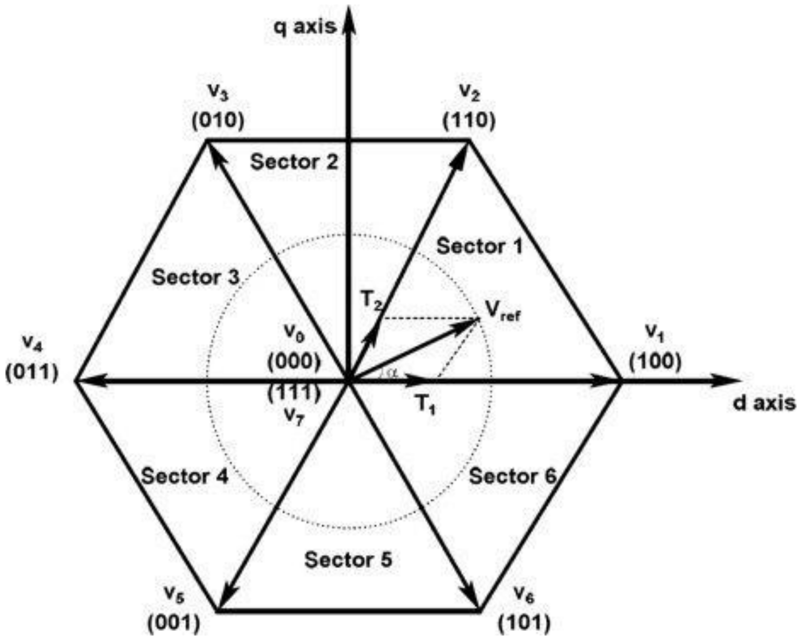

Figure 3.a: The Basic switching vectors and sectors.

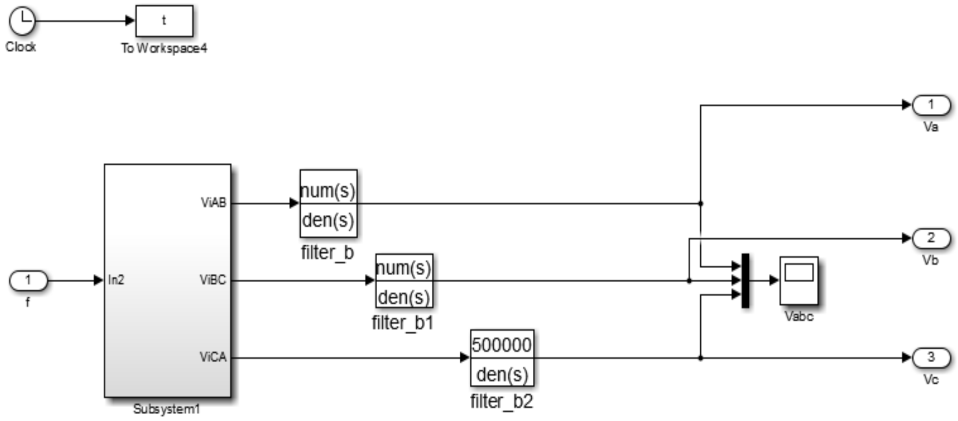

Figure 3.b: Model of SVPWM.

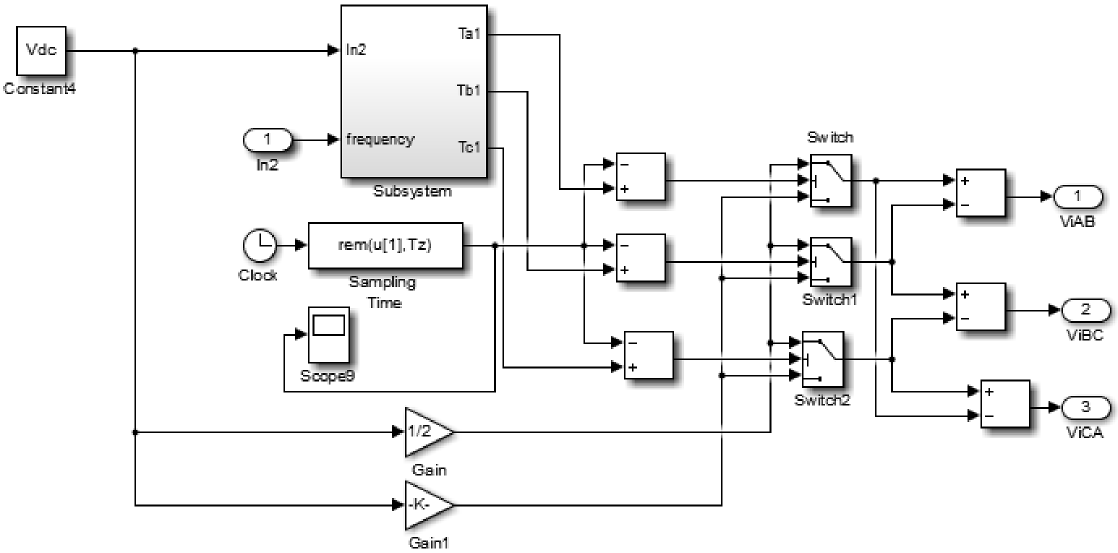

Figure 3.c: Model of SVPWM.

4. PI CONTROLLER

The conventional Proportional Plus Integral controller (PI) is the simple speed controller in industrial applications. Under the load condition, the PI controllers try to modify the motor speed to attain the desired system speed. The output of the PI controller is function of the speed error and the integral of error:

$$u\,(t) = K_p\ \ e(t) + K_i \int e\,(t)\,d(t) \qquad \textbf{(12)}$$

5. SLIDING MODE CONTROLLER:

The overall scheme of SMC is shown in **Fig.4** below, Generally, the mechanical equation of an IM can be presented as follows:

Patakor, et al, 2010, and Bennassar, et al., 2013.

$$T_e\ = J\dot{\omega}_m + B\omega_m + T_L \qquad (13)$$

Where B is the friction factor of the IM , T_L is refer to the external load torque , ω_m is the mechanical speed of the rotor , and T_e is point to the electromagnetic torque which can be represented in Eq. (9) as :

$$T_e\ = \frac{3}{2}\left(\frac{P}{2}\right)\left(\frac{L_m}{L_r}\right)\left(\Psi_{dr}i_{qs}\ -\ \Psi_{qr}i_{ds}\right) \qquad (9)$$

According to the FOC principle , the current component i_{ds} is line up the direction of the rotor flux vector Ψ_r and the current vector i_{qs} is line up perpendicular to it , so the flux vector , $\Psi_{qr} = 0$, $\Psi_{dr=} |\Psi_r|$, and the Eq.(9) become :

$$T_e\ = \frac{3}{2}\left(\frac{P}{2}\right)\left(\frac{L_m}{L_r}\right)\left(\Psi_{dr}i_{qs}\right) =\ K_T\, i_{qs} \qquad (14)$$

Where $\boldsymbol{K_T}$ is the torque constant , and it defined as follow :

$$\boldsymbol{K_T} = \frac{3}{2}\left(\frac{P}{2}\right)\left(\frac{L_m}{L_r}\right)\left(\Psi_{dr} i_{qs}\right) \qquad (15)$$

Using Eq. (14) into (13) then we can get

$$\boldsymbol{b i_{qs=}\ \dot{\omega}_m + a\omega_m + f} \qquad \textbf{(16)}$$

Where $\boldsymbol{a} = \frac{B}{J}$, $\boldsymbol{b} = \frac{K_T}{J}$ and $\boldsymbol{f} = \frac{T_L}{J}$

Eq.(16) can be presented with uncertainties $\Delta\boldsymbol{a}$ **,** $\Delta\boldsymbol{b}$ **and** $\Delta\boldsymbol{f}$ **,** as follow :

$$\boldsymbol{\dot{\omega}_m} = -(\boldsymbol{a} + \Delta\boldsymbol{a})\boldsymbol{\omega_m} - (\boldsymbol{f} + \Delta\boldsymbol{f}) + (b + \Delta\boldsymbol{b})\boldsymbol{i_{qs}} \qquad \textbf{(17)}$$

The error of the tracking speed can be defined as

$$\boldsymbol{e_{(t)=}\ \omega_m(t) - \omega_m^*\,(t)} \qquad \textbf{(18)}$$

Where $\boldsymbol{\omega_m^*\,(t)}$ is point to rotor reference speed , taking the derivative of the pervious equation with respect to time produce :

$$\dot{e}_{(t)=}\ \boldsymbol{\dot{\omega}_m(t) - \dot{\omega}_m^*\,(t)} = -\,\boldsymbol{a\, e(t) + u(t) + d(t)} \qquad \textbf{(19)}$$

Where

$$\boldsymbol{u\,(t) = b i_{qs} - a\dot{\omega}_m - f - \dot{\omega}_m^*\,(t)} \qquad \textbf{(20)}$$

and the equation of the uncertainties can be represented as:

$$\boldsymbol{d\,(t) = -\Delta a\dot{\omega}_m - \Delta f(t) - \Delta b i_{qs}\,(t)} \qquad (\textbf{21})$$

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

$$\boldsymbol{S\,(t) = e(t) - (k - a) \int e\,(t)\; d(t)} \qquad \textbf{(22)}$$

Where $\boldsymbol{k}$ is a constant gain and it defined as $k<0$. When the sliding mode occurs on the sliding surface, then $S(t) = \dot{S}(t) = 0$, therefor the dynamic behavior of the tracking problem can be illustrated as

$$\dot{e}_{(t)} = \boldsymbol{(k - a)\, e(t)} \qquad \textbf{(23)}$$

The variable structure speed controller is designed as:

$$\boldsymbol{u\,(t) = k\, e(t) - \beta sgn(S)} \qquad (\textbf{24})$$

Where β is known as the switching gain , S is the sliding variable and sgn(.) is the sign function which can be defined as :

$$\text{Sgn}\,(S\,(t)) = \begin{cases} 1 & if\ S(t) > 0 \\ -1 & if\ S(t) < 0 \end{cases} \qquad (25)$$

Finally the current i_{qs} can be obtained by directly substituting u (t) expressed in Eq.(24) in the previous Eq. (16) , .

$$i_{qs} = \frac{1}{b}(k\,e(t) - \beta sgn(S) + a\omega_m^* + \dot{\omega}_m + f\,) \qquad (26)$$

From Eq. (11) and (26)

$$\omega_{sl} = \frac{c}{b}(k\,e(t) - \beta sgn(S) + a\omega_m^* + \dot{\omega}_m + f\,)\ i_{qs} \qquad (27)$$

Where c is the constant , so by using the above sliding mode design , the speed tracking problem will be solved under the load disturbance , The chattering phenomenon is eliminated in the SMC systems by using saturation functions $sat(\,)$ instead of sign function $sgn(\,)$ in Eq. (27) , **Sulaiman, et al., 2014** .

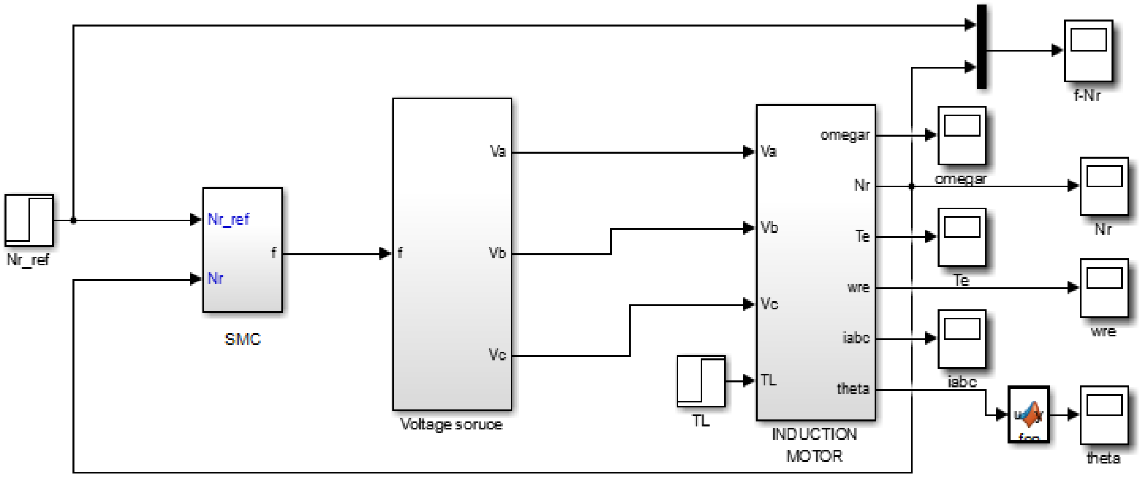

Figure 4. SMC design.

5. SIMULATION RESULTS

The Simulation of the controller are done on IM with the parameters shown in **Table 1**. **Fig.5** show the speed response of the SMC when sign function is used where chattering phenomenon is present , chattering can be removed by using saturation functions $sat(\,)$ instead of sign function $sgn(\,)$ as shown in **Fig. 6,7, and 8** which show the speed , current and the torque responses of IM when the speed is varied from 1500 to1377 rpm at time 3 sec. after applying external load torque = 4N.m with SMC. The phase plane portrait of the speed error is shown in **Fig.9**. It is clear that the error trajectory moves toward the equilibrium point and after loading of IM the trajectory leaves the equilibrium point and the SMC will overcome this change.

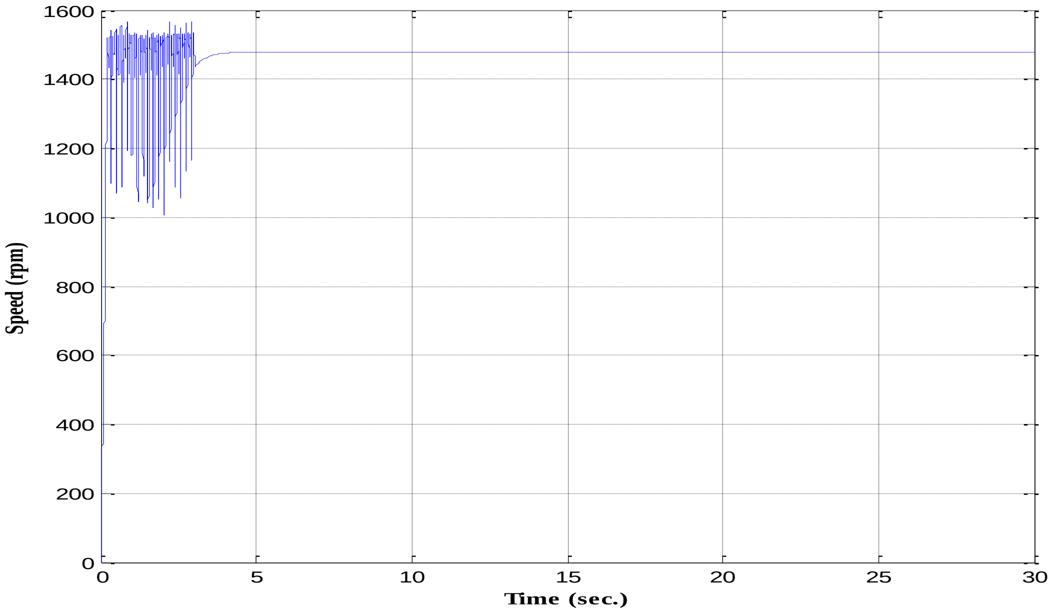

Figure 5. Speed response with sgn function .

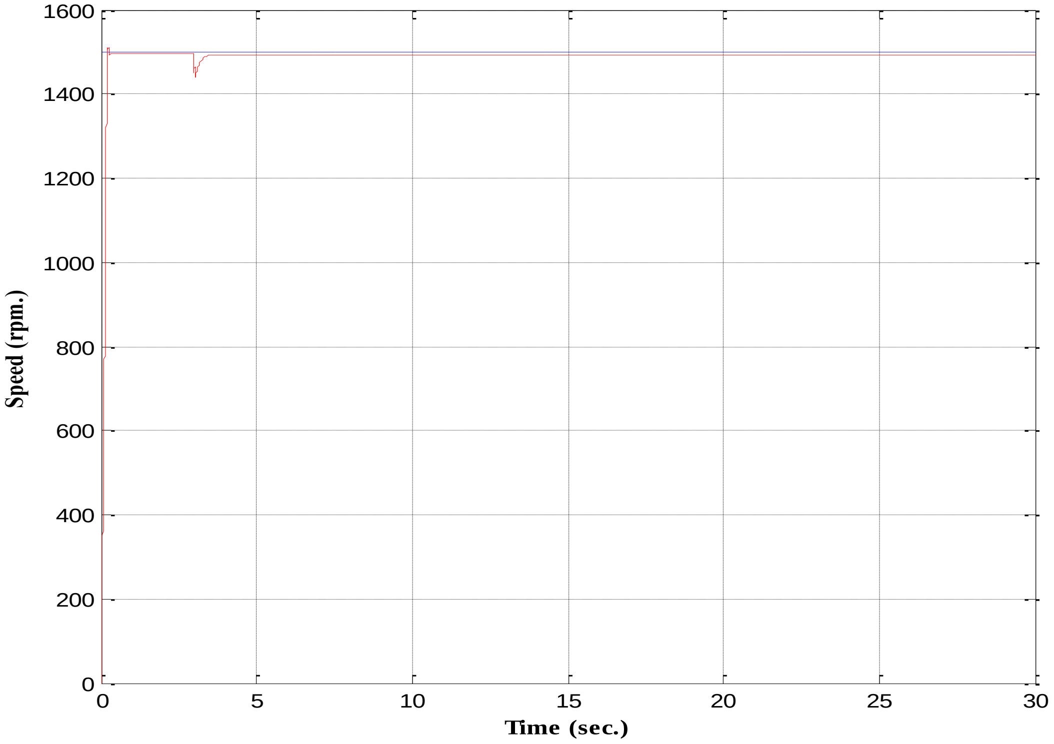

Figure 6. Speed response.

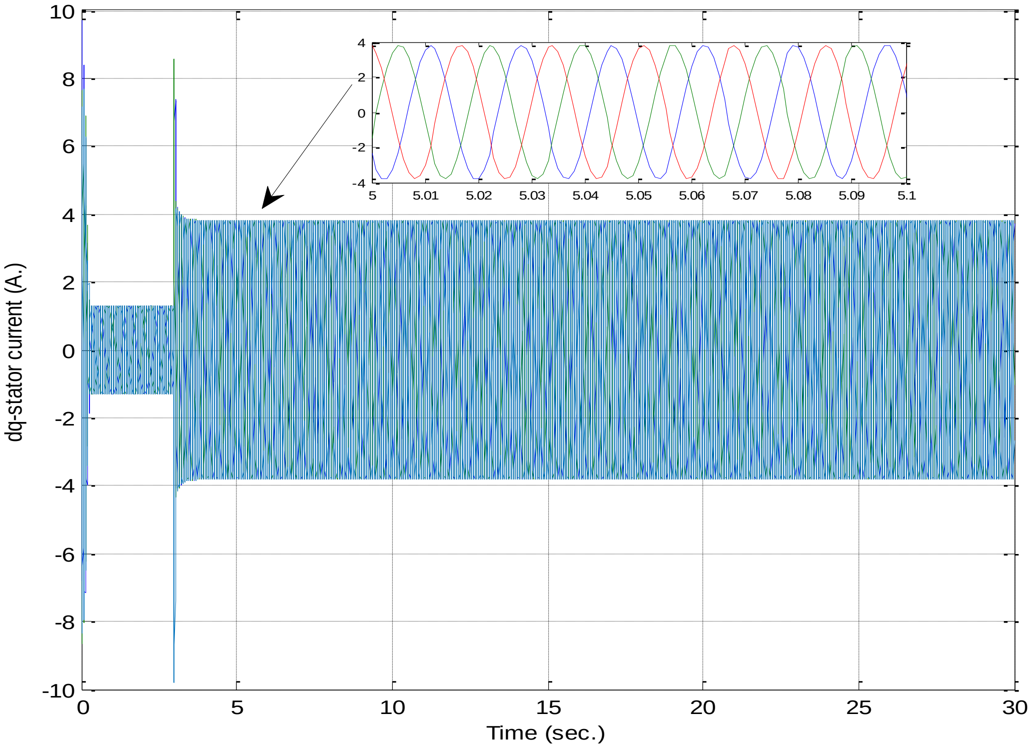

Figure 7. dq-Stator Currents response.

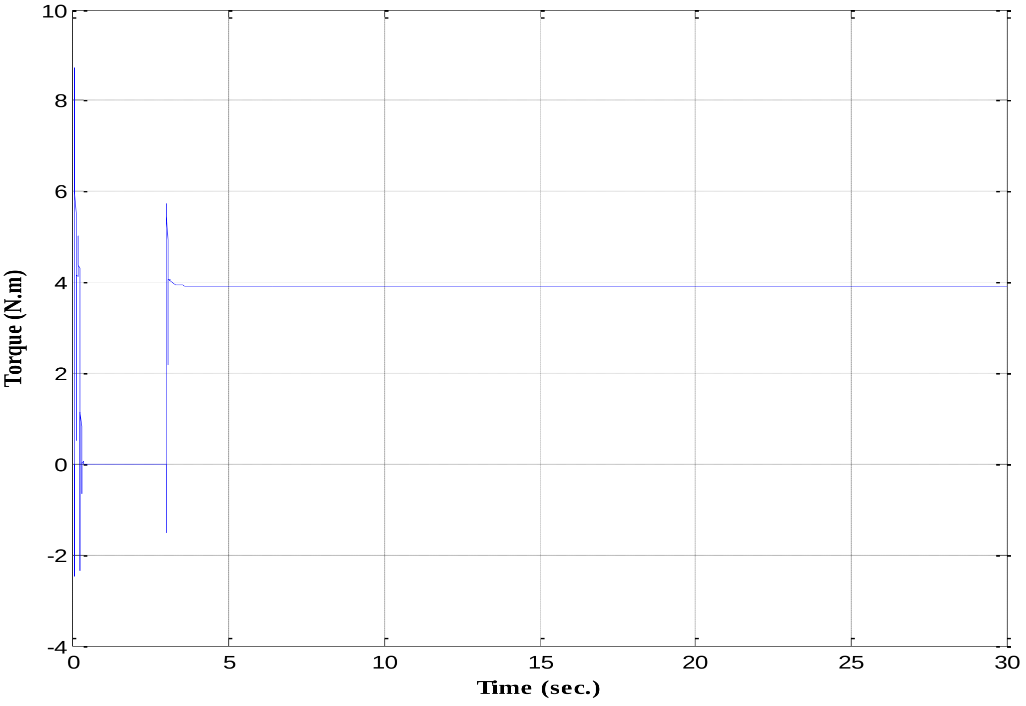

Figure 8. Torque response.

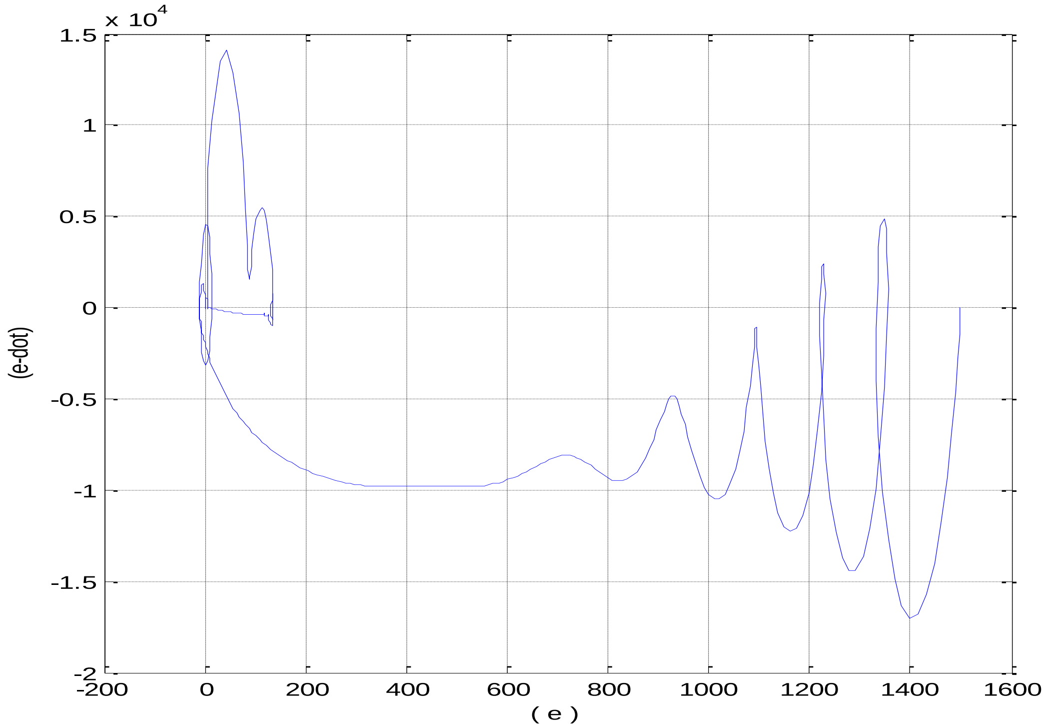

Figure 9. The phase plane portrait of the speed error.

Fig.9 shows the system trajectory that start from the point ($e, \dot{e}$) = (1500,0) and move towards the equilibrium point (0,0) with some delay .at loading instant the motor speed is decreased and the error is increased which affect the system trajectory and leave the equilibrium point ,the used controller try to return it back to that point .

Fig.10 shows the speed responses of IM with conventional PI controller. At the load instant the motor speed is decreased from 1496 rpm to 1374 rpm. The results show that the SMC can provide better and robust speed tracking performance when it compared with conventional PI controller.

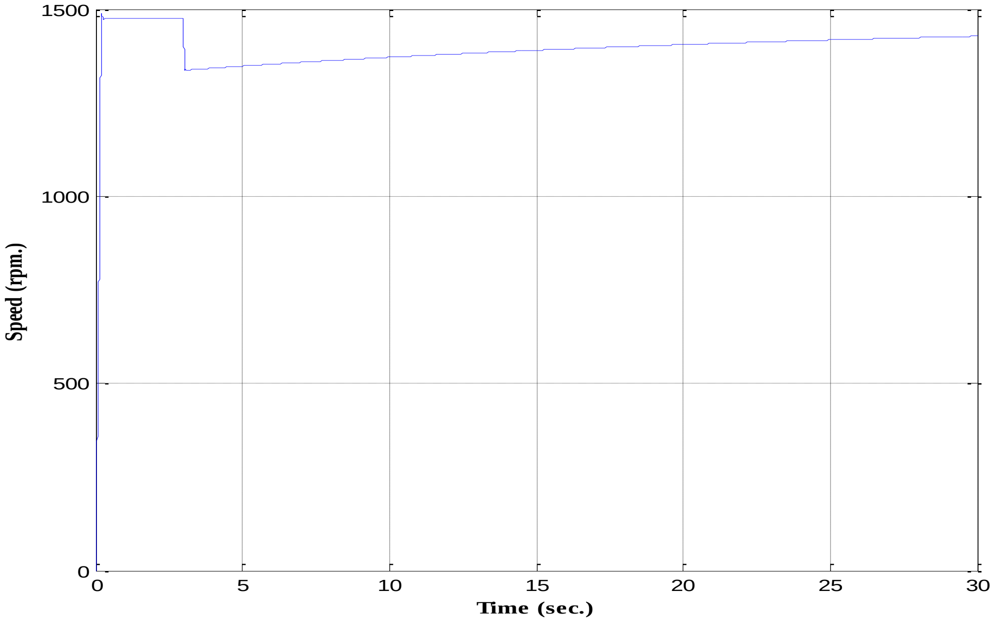

Figure 10. Speed response**.**

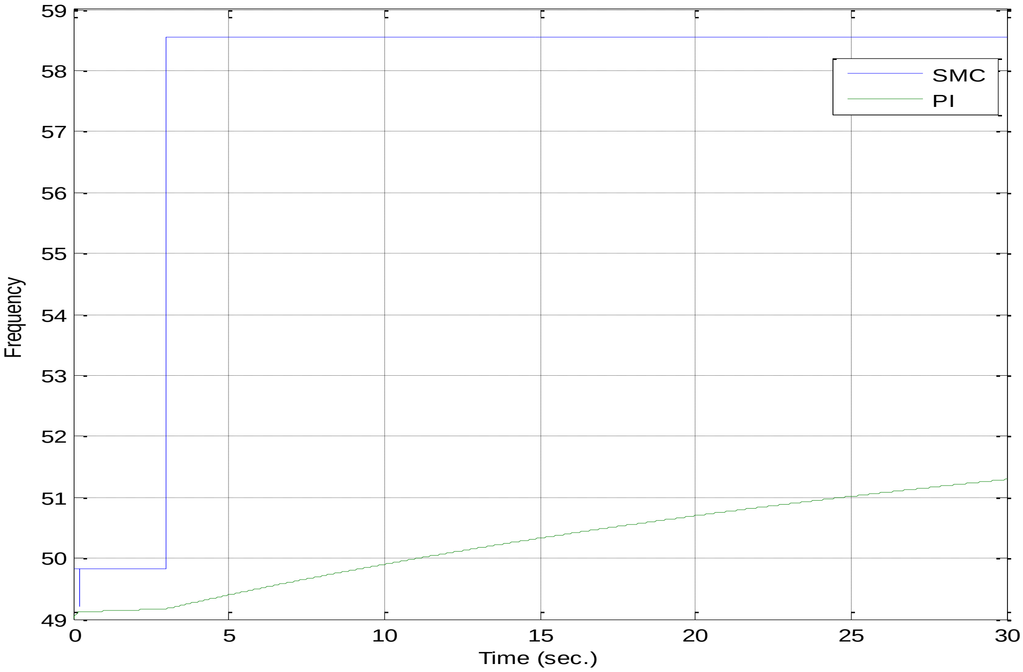

Figure 11. frequency of SMC and PI**.**

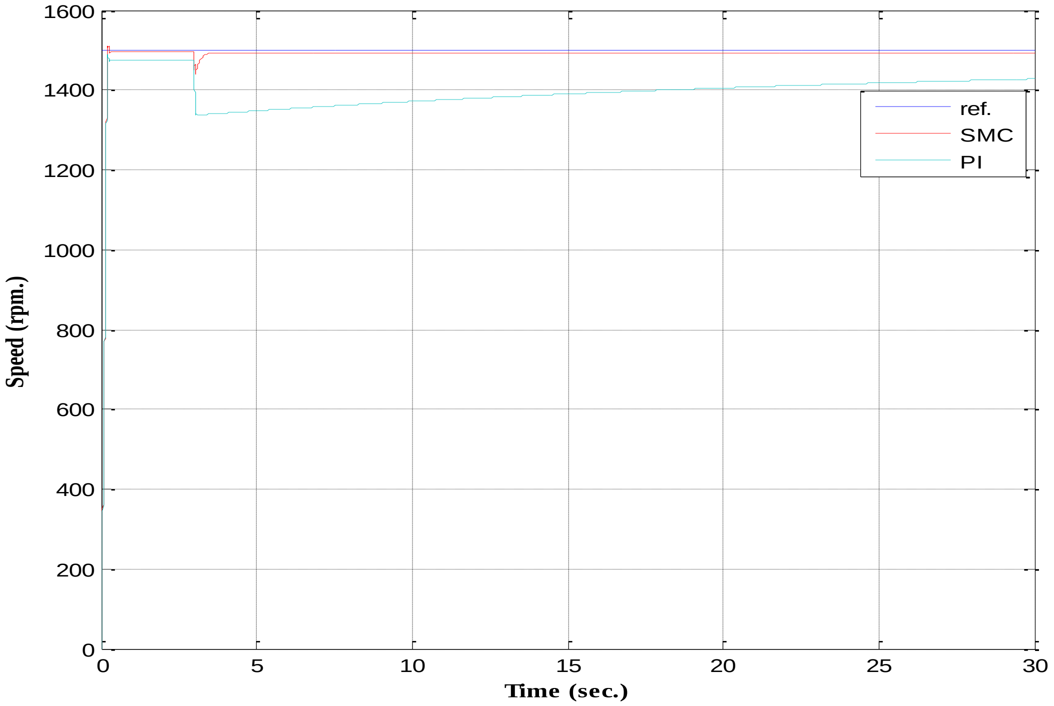

Figure 12. Speed response of SMC and PI**.**

Table 1. Parameters of IM.

Parameters	**Values**	**Units**
Voltage (V.)	220	V
Stator resistance (Rs)	6.03	Ω
Rotor resistance (Rr)	6.085	Ω
Stator inductance (Ls)	489.3e-3	H
Rotor inductance (Lr)	489.3e-3	H
Mutual inductance (Lm)	450.3e-3	H
Poles (p)	4	---
Inertia (J)	0.00488	Kg.m^2
Friction (B)	0.0003	Nm/(rad/s)

Fig.11 shows the frequency response from the controller, it can be recognized that the frequency increases after applying the load, the SMC controller raised the frequency more quickly than the PI controller. The result obtained in **Fig.12** show a comparison between the reference speed and both the SMC and PI controller and it show that the SMC can provide better and robust speed tracking performance when it compared with PI controller where the motor start with speed =1500 rpm. then after applying external load the speed falls and the SMC return it back to the actual speed, un like the result of the PI controller where the controller is attempt to improve the system response and push up the speed to 1500 rpm, but it takes more time to reach the motor reference speed.

6. CONCLUSION

In this paper an adaptive SMC with integral sliding surface is presented and FOC strategy is used. The proposed SMC will overcome the load change faster than the conventional PI controller with zero steady state error. SMC consists of two parts. The first part is reaching phase that moves the system from the initial condition to the sliding surface. While the second part is sliding phase which tries to fix the system to sliding toward the equilibrium point. The frequency result from the controller increase when the load is applied, while the speed decreases and the controller used attempt to raise it to reference speed, chattering that occurs in the sliding phase can be overcomes by using saturation function. Therefore, the SMC is intelligent controller operating under uncertainty conditions and deals with the system changes quickly.

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NOMEN CLATURE

B = coefficient of viscous friction , Nm/(rad/s)

$\boldsymbol{i_{ds}}$, $\boldsymbol{i_{qs}}$ = direct and quadrature axis components of stator currents , Amp.

J = moment of Inertia , Kg.m^2

k = constant gain , dimentionless

L_s , L_r & L_m = stator, rotor and mutual inductances. H

P = number of poles.

R_S = stator resistance of Induction motor. Ω

R_r = rotor resistance of Induction motor. Ω

S(t) = sliding surface. Dimentionless

T_e = torque developed in the Induction motor. N.m

T_L = external load torque . N.m

Vds , Vqs = direct and quadrature axis components of stator voltages , Volt.

ωr = rotor speed, rad/sec.

ωe = synchronous speed, rad .sec

ωsl = slip speed. rad .sec

β = switching gain , dimentionless

Ψ_{dr} Ψ_{qr} = direct and quadrature axis components of rotor flux. Wb