Parameter Compensation of Induction Motor Drives using Second order of Sliding Mode Controller

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Abstract: - The continued operation of vector controlled induction motor drives faces problems related to the stator and rotor resistance variation due to saturation, skin effect or in temperature variations. These resistance variations affect the controller performance. This paper illustrates a new closed-loop approach for evaluation followed by compensation of stator and the rotor resistance of an induction motor by using the method of second-order sliding mode controller. The motor resistances estimated by online and the fault between the actual and the desired state variables of the motor track the sliding surface, the proposed method is established on the rigorous Lyapunov stability criteria. The simulation results show that the high-frequency variation in output waveform is reduced as compared to classic sliding mode controller and the mathematical analysis which is simple and reduces the complexity facedby the higher order controller. For the estimation of the control variables of the proposed algorithm, only current measurement is needed and the controller is independent of the unknown parameter variation as the property of the sliding mode controller. The proposed method has been analyzed and verified with the help of Matlab/Simulink.

Keywords: - Induction Motor (IM), Sliding Mode Controller (SMC), Parameter, Compensation, Estimation.

1- Introduction

Induction motor drive is now acquiring an enormous attention in the field of electric drive as well as in dynamic control due to its high dynamic response and its low cost. The vector controlled method is generally used due to its simplicity and fast response. The dynamic model of an induction motor is precisely nonlinear, so having control over induction motor is a challenging problem which attracted much attention. Moreover, with the operation of the drives, the parameters (resistance and inductance) vary due to saturation, skin effect or in variations in the temperature. In vector controlled induction motor drives the variation in inductance is negligible because it operates at constant flux, so only resistance of rotor and stator windings are variable. The performance of the drives influenced by the variation of the resistances to omit this problem and improve the performance of the drive in which the controller schemeis independent of the variation in parameters or develop some algorithm that can estimate and compensate parameters simultaneously. Rotor and stator resistance of the induction motor varies with the temperature variation due to motor heating, many researchers develop an algorithm to predict the stator resistance [1]-[3] by using the microcontroller and online estimation but these are unstable in low-speed range or the regenerative mode of the electric drives. Evaluation of rotor resistance of the induction motor is important because it strongly influenced the speed of induction motor. Rotor resistance estimated by using Reactive power error method, by torque error method and by error function based on stator voltage [4]-[7] these techniques take the large converge time and a large harmonics present in the supply voltage that fluctuates the estimated parameters. Although all the above techniques estimate the stator or a rotor resistance individually whereas the controller performance affects by variation of a stator and a rotor resistance both, so for improving the zof the controller both stator and rotor resistance estimation require. In papers [8]-[10] both stator and rotor resistances are evaluated, mainly uses online and observer-based methods, these methods are complex it bounded the stator current. Fuzzy logic and artificial neural network are also used to estimate the rotor and stator resistances but in these methods, proper designing of fuzzy rules and the adjustment of the weight is required [11]-[14]. Even many optimization methods like agenetic algorithm, partial swam optimization methods are also used to estimate the resistance of induction motor but all these optimization methods are offline methods[15]-[18]. In the real world application, any optimization technique requires a long time to run and a large memory and it is impossible to find the exact result, the result can be only near the global extreme.

Sliding mode controller (SMC) is a robust controller, that is uncertain with the parameter variation. Most of the researchers use SMC observer for estimation the stator and rotor resistances [19]-[22] but they are higher order, due to this the complexity of the system increases. Even the classical SMC technique is also applied to evaluate the resistance of the IM in the sensorless IM control drives [23]. The classical SMC faces the problem of chattering [24]-[25]. Many researchers work on to eliminate the chattering[26]. In recent years a robust software sensor for the IM drives is developed for evaluation of the stator resistance that improves the performance of the drives [27] but that software only estimates the stator resistance.

In this paper a second order SMC with the new proposed control law based on Lyapunov stability theory [28] is used to estimate and also compensate of the rotor and stator resistance, using online adaptation method. The singular perturbation theory is used to reduce the order of the induction motor from fifth order to second order [29]-[31] and the second order SMC in place of 9th or higher order decreases the complexity of the system and makes it simple. The chattering problem is mitigated with the use of the second order SMC.

The paper is organized as,Section I which is the introduction that briefs about the paper, Section II preface the model of the induction motor, Section III describe the proposed parameter compensation technique using second-order sliding mode controller, Section IV presents the simulationmain block with the subsystems of the proposed algorithm. The results of the simulation also present in the section IV that verify the proposed method. Finally, the conclusion is given in the last Section V of the paper.

2. Mathematical Modelling of Induction motor

The Mathematical model of theinduction motor is the dq coordinatewhich is given by [32].

$$\frac{d}{dt}\begin{bmatrix} i_{ds} \\ i_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} = \begin{bmatrix} -a_1 & \omega_e & a_2 & a_3\omega_r \\ -\omega_e & -a_1 & a_3\omega_r & a_2 \\ a_5 & 0 & -a_4 & \omega_{sl} \\ 0 & a_5 & -\omega_{sl} & -a_4 \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} + \begin{bmatrix} c & 0 \\ 0 & c \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} \quad (1)$$

$$T_e - T_L = J\frac{d\omega_m}{dt} + B\omega_m \quad (2)$$

where (i_{ds}, i_{qs}), (v_{ds}, v_{qs}), (ψ_{dr}, ψ_{qr}) are stator current, stator voltage, and rotor flux respectively, theyare normalized by the mutual inductance L_m in dq coordinate. Whereas ω_r,T_e, T_L and $\omega_e$arerotor speed (rad/s), motor torque (Nm), load torque (Nm)&angular frequency of stator current(rad/s) respectively.

Where, $a_1 = \frac{1}{\sigma L_s}\left(R_s + {R_r L_m}^2 / {L_r}^2\right)$;

$$a_2 = \frac{1}{\sigma L_s} {R_r L_m}^2 / {L_r}^2$$

$$a_3 = \frac{1}{\sigma L_s} L_m / L_r;\ a_5 = R_r L_m / L_r;\ a_4 = R_r / L_r;$$

$$c = \frac{1}{\sigma L_s}$$

$$\omega_{sl} = \omega_e - \omega_r;\ \omega_{sl} = a_5 \frac{i_{qs}}{\psi_{dr}} \quad (3)$$

R_s is the stator resistance, $R_r$the rotor resistance, $L_s$is stator inductance, L_r is rotor inductance, L_m is mutual inductance, p the number of pole pairs, and J the moment of inertia of therotor.

As we can see from equation (1) and (2), the mathematical equation of the induction motor is nonlinear and isin the fifth order of equation, in which many variables are known. To make a system simpler the singular perturbation theory is used to reduce the order of the induction motor [29-31]. According to that theory, the part of the system which operated at slower speed assumes as constant. In induction motor drive system the mechanical dynamics operated at much slower speed as compared to the current dynamics and electromagnetic dynamics. So, the flux and rotor speed assumed to be constant and drive the state space equation of induction motor as given in equation (4). Order of the equation reduces to second order in which the states of the equations are only the d-axis stator and q-axis stator currents.

$$\frac{d}{dt}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = \begin{bmatrix} a_1 & \omega_e & a_2 & a_3\omega_r \\ -\omega_e & a_1 & -a_3\omega_r & a_2 \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} + \begin{bmatrix} c & 0 \\ 0 & c \end{bmatrix}\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} \quad (4)$$

In field orientated control of induction motor, to achieve field orientation, the q-axis torque component perpendicular to the rotor flux, and the d-axis flux component aligned in the direction of it. At this condition:

$$\psi_{qr} = 0 \text{ and } \psi_{dr} = \psi_r = L_m i_{ds} \quad (5)$$

Let the two control parameters u_1 and u_2 define as given below that can simplify the equation

$$u_1 = -\frac{R_s}{\sigma L_s} \text{and} \quad u_2 = \frac{R_r}{L_r} L_m \quad (6)$$

Therefore the equation (4) becomes

$$\frac{d}{dt} i_{ds} = u_1 i_{ds} + u_2 \frac{i_{qs}^2}{\psi_{dr}} + \omega_r i_{qs} + \frac{v_{ds}}{\sigma L_s} \quad (7)$$

$$\frac{d}{dt} i_{qs} = u_1 i_{qs} - u_2 \frac{i_{qs}}{\sigma L_m} - \frac{\omega_r}{\sigma} i_{ds} + \frac{v_{qs}}{\sigma L_s} \quad (8)$$

As from equation (6) that the rotor and stator resistances estimated by the control parameters u_1 and u_2. After estimation, the resistances are compensated by the controller.

3 Proposed Sliding Mode Controller Design

The controller is designed to find control parameters u_1 and u_2 in such a way that the error arises between the actual and the evaluated values of d-axis and q-axis stator currents will be zero. The estimated currents are obtained from equations. (7) and (8) as given below.

$$\dot{\hat{i}}_{ds} = \hat{u}_1 \hat{i}_{ds} + \hat{u}_2 \frac{i_{qs}^2}{\psi_{dr}} + \omega_r \hat{i}_{qs} + \frac{v_{sd}}{\sigma L_s} \quad (9)$$

$$\dot{\hat{i}}_{qs} = \hat{u}_1 \hat{i}_{qs} - \hat{u}_2 \frac{i_{qs}}{\sigma L_m} - \frac{\omega_r}{\sigma} \hat{i}_{ds} + \frac{v_{sd}}{\sigma L_s} \quad (10)$$

The sliding mode controller operated in such a way that the error "e", as well as its rate of change of "e", moves towards the sliding surface. The Sliding surface can be obtained by the use of Lyapunov stability theory.

Lyapunov stability theorem: It states that: "If the projection of the system trajectories on sliding surfaces remains stable then the system is also stable. Thus the theorem can be formulated as:

Theorem: if a scalar function V(x) exists which is real, continuous and has continuous first partial derivatives with $V(x) > 0 \; for \; x \neq 0; \; V(0) = 0$

And its derivative $\dot{V}(x)$ *is negative everywhere except the discontinuity surface then, the system is stable."*

There is no specific method to find the Lyapunov function. However, V.I. Utkin [33] has discussed the method of using quadratic forms to find the sliding domain.

Generally, Lyapunov function choose as $V = \frac{1}{2} e^T e$

$$\text{where} \quad e = \begin{bmatrix} i_{ds} - \hat{i}_{ds} \\ i_{qs} - \hat{i}_{qs} \end{bmatrix} \quad (11)$$

$$\dot{V} = e^T \dot{e} = e^T \begin{bmatrix} \dot{i}_{ds} - \dot{\hat{i}}_{ds} \\ \dot{i}_{qs} - \dot{\hat{i}}_{qs} \end{bmatrix} \quad (12)$$

Substituting the values of actual and estimated stator currents from equations (7), (8), (9) and (10), in equation (12) for obtaining the expression of $\dot{V}$

$$\dot{V} = e^T \dot{e} = e^T A e + e^T B e_u \quad (13)$$

where

$$\dot{e} = \begin{bmatrix} u_1 & \omega_r \\ -\frac{\omega_r}{\sigma} & u_1 \end{bmatrix}\begin{bmatrix} i_{ds} - \hat{i}_{ds} \\ i_{qs} - \hat{i}_{qs} \end{bmatrix} + \begin{bmatrix} \hat{i}_{ds} & \frac{i_{qs}^2}{\psi_{dr}^*} \\ \hat{i}_{qs} & \frac{i_{qs}}{\sigma L_m} \end{bmatrix}\begin{bmatrix} u_1 - \hat{u}_1 \\ u_2 - \hat{u}_2 \end{bmatrix} \quad (14)$$

$$A = \begin{bmatrix} u_1 & \omega_r \\ -\frac{\omega_r}{\sigma} & u_1 \end{bmatrix}, B = \begin{bmatrix} \hat{i}_{ds} & \frac{i_{qs}^2}{\psi_{dr}^*} \\ \hat{i}_{qs} & \frac{i_{qs}}{\sigma L_m} \end{bmatrix}, e_u = \begin{bmatrix} u_1 - \hat{u}_1 \\ u_2 - \hat{u}_2 \end{bmatrix}$$

Let us assume that $\begin{bmatrix} i_{ds} - \hat{i}_{ds} \\ i_{qs} - \hat{i}_{qs} \end{bmatrix} = \begin{bmatrix} ei_{ds} \\ ei_{qs} \end{bmatrix}$

As per the Lyapunov stability theorem, $\dot{V}$ is negative everywhere for the stability of the system. The first term in equation (14) is negative as A matrix is negative definite and the second term prove to be negative, which is given by

$$e^T B e_u = [ei_{ds} \quad ei_{qs}] \begin{bmatrix} \hat{i}_{ds} & \frac{i_{qs}^2}{\psi_{dr}^*} \\ \hat{i}_{qs} & \frac{i_{qs}}{\sigma L_m} \end{bmatrix}\begin{bmatrix} u_1 - \hat{u}_1 \\ u_2 - \hat{u}_2 \end{bmatrix} \quad (15)$$

The problem in tracking is similar to the remaining sliding surface for all times, and sliding variable is to be kept zero. We choose the sliding surfaces such that $e^T B e_u = 0$. Switching surface is a line in the second-order system. Control input is applied to drive the system state over the switching line, and at once the system is constrained to remain on the line.

For deciding control input, two parameters are used i.e. the distance of error trajectory from the sliding surface and also its rate of convergence. The sign of the control input must change where the tracking error trajectory intersects with the sliding surface. In this way, the error trajectory is enforced to always move towards the sliding surface. Once it arrives at the sliding surface then, the system is constrained to slide along this surface to equilibrium point. For estimation of u_1 and u_2 the sliding surface, S_1 and S_2 are selected as given below respectively.

$$s = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} = \begin{bmatrix} ei_{ds}\hat{i}_{ds} + ei_{qs}\hat{i}_{qs} \\ ei_{ds}\frac{i_{qs}^2}{\psi_{dr}^*} - ei_{qs}\frac{i_{qs}}{\sigma L_m} \end{bmatrix} \tag{16}$$

The main drawback of the sliding mode controller (SMC) in real time application is the chattering problem to remove or reduce the chattering in the control, the order of the controller must be greater than one. In the proposed algorithm a Quasi-second order SMC is chosen because it provides the continuous control everywhere except the manifold, as a result the chattering effect reduces.

A Quasi-second order SMC provides the full SISO control based on the input measurement only.The homogeneous differentiator can be defined as [34].

$$\dot{z_o} = -\lambda_\delta L^{1/\delta}|z_o - s|^{((\delta-1)/\delta)} sign(z_0 - s) + z_1 \tag{17}$$

$$\dot{z}_{\delta-1} = -\lambda_1 L sign(z_{\delta-1} - \dot{z}_o) \tag{18}$$

Where δ is the order of the system. As from equation (4), the order of the system is second; $\delta = 2$ means the first derivative of the s is the need.

As $\delta = 2$,

$$\dot{z_o} = -\lambda_2 L^{1/2}|z_o - s|^{(1/2)} sign(z_0 - s) + z_1 \tag{19}$$

$$\dot{z}_1 = -\lambda_1 L sign(z_1 - \dot{z}_o)$$

Where $\lambda_2 L^{1/2}$ and $\lambda_1 L$ are positive constantand $\dot{s} = z_1$.

The differentiator in equation (19) is used to derived the second order sliding homogeneous control signals is obtained as

$$\hat{\dot{u}} = \frac{-\alpha\left(\dot{s} + |s|^{1/2} sign(s)\right)}{\left(\left|\dot{s} + |s|^{1/2}\right|\right)} \tag{20}$$

Where and α is a positive constant.

By integrating the equation (20) we get the estimated values of the control parameter and indirectly the stator and the rotor resistance.

The suggested algorithm is uncertain with parametric variations of the system and due to the higher order, high-frequency noise is also reduced. The block diagram of the proposed algorithm is shown in figure 1.

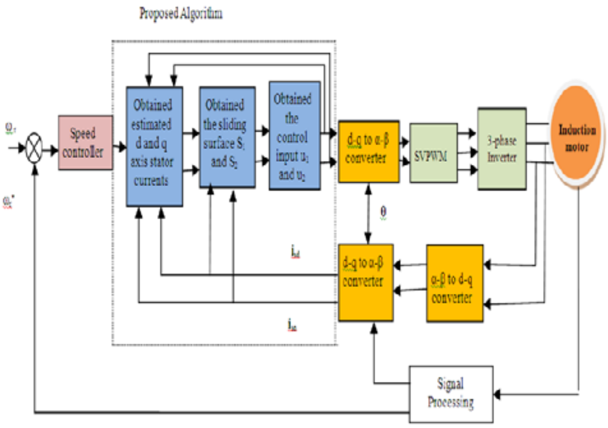

Fig.1 Block Diagram with Proposed Algorithm

4 Simulation and Result

Matlab/Simulink is used to simulate the proposed controller. The simulation model and the results are presents in this section. Table I specified the machine parameters which are used in the simulation. Figure 2 shows the overall Simulink model of theproposed controller alongthe induction motor. There are four subsystems in this model out of which one is the vector control block, the interior of this subsystem is shown in figure 3 from this Simulink block generated the control pulse for the inverter. The second one is the subsystem1 shown in figure 4 from this the sliding surface for the sliding mode controller is generated, according to this sliding surface the two control signal u_1 and u_2 by using equation (20) form, the Simulink block of this is shown in figure 5. These control signals signify the estimated values of the stator and the rotor resistance as shown by equation (6). The other subsystem in the main Simulink model is the subsystem3 that represent the control unit of the proposed system. The interior of the subsystem3 is representing in figure 6.

TABLE I
INDUCTION MOTOR PARAMETERS

Parameters	Notation	Values
Rotor resistance	R_r	4.3047 Ω
Stator resistance	R_s	6.65 Ω
Mutual inductance	L_m	0.4475 H
Stator inductance	L_s	0.4718 H
Rotor inductance	L_r	0.4718 H
Rotor inertia	J	0.0293 kg/m^2
Pole pair	p	2

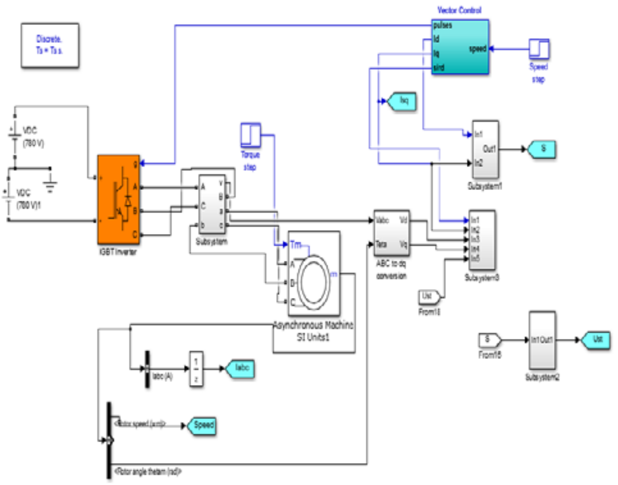

Fig.2 Simulation Model of Induction motor with proposed controller

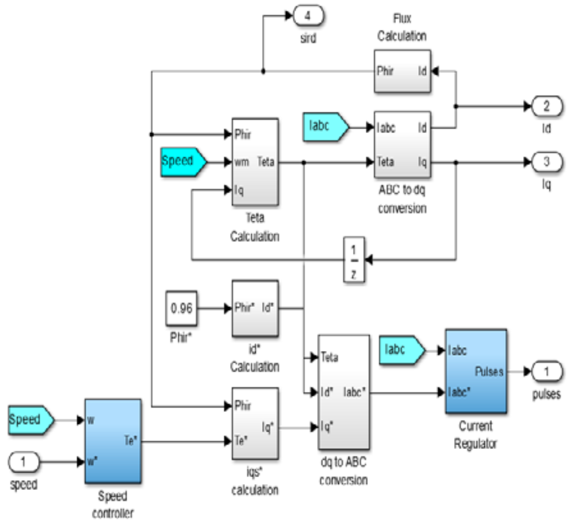

Fig.3 Subsystem of Vector control

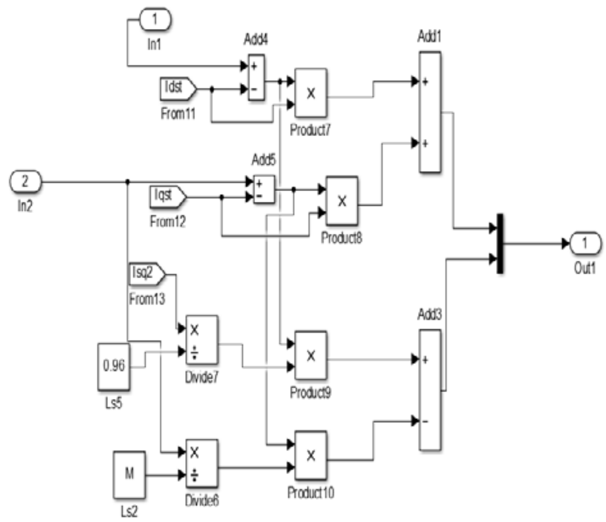

Fig.4 Subsystem1 of sliding surface S

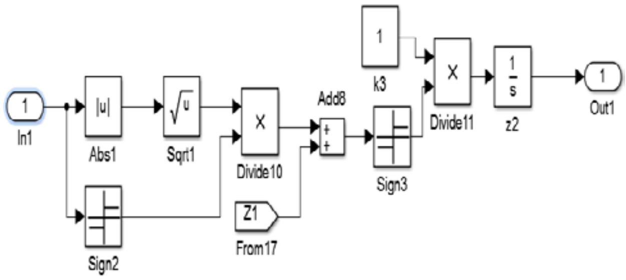

Fig.5 Subsystem2 for control parameter $u_1$and u_2

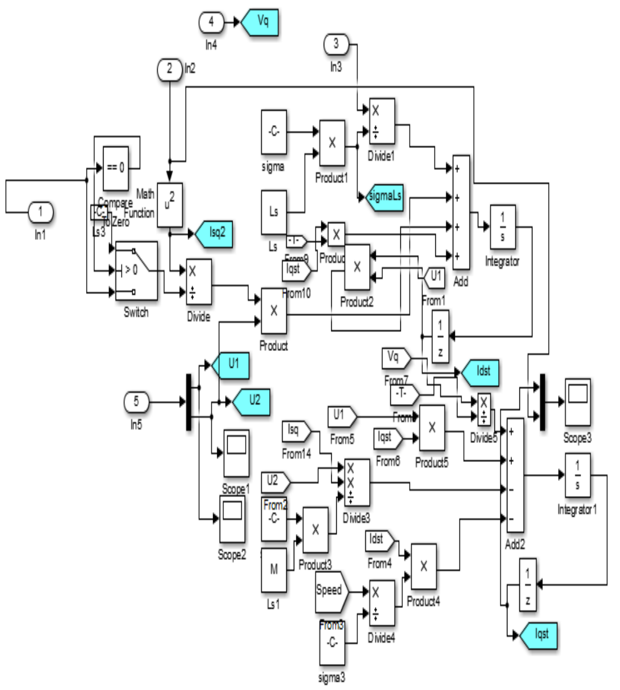

Fig.6 Subsystem3 control block

The induction motor runsat a constant speed letting it be 30 rad/s after 2 sec. Load torque of 2 Nm is applied during this time, the flux is established and attains a constant value in the machine. As observed in figure 7 and 8 the sliding surface $S_1$and $S_2$are reached then they are maintained even the parameters of the machines changed. By using estimated values of the control signal u_1 and u_2 as shown in figure 9 and 10 respectively, the values of stator and rotor resistances are calculated. The evaluated and actual values of the stator d and q-axis current shown in figure 11,12,13 and 14. The sliding surface not altered after reached, that certify the proposed method for compensation and estimation of machine parameters.

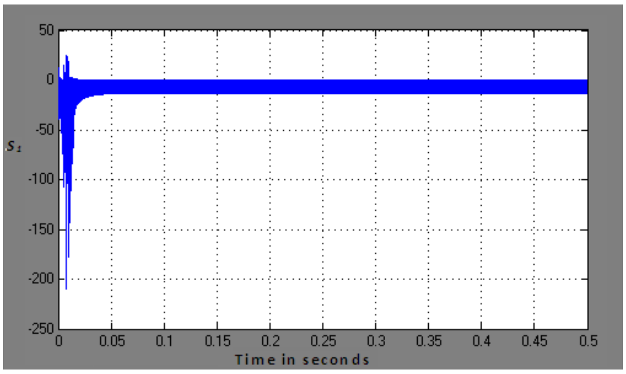

Fig. 7 The Sliding Surface S_1

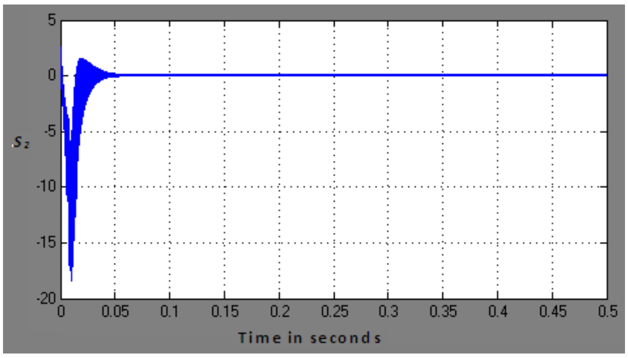

Fig.8. The Sliding Surface S_2

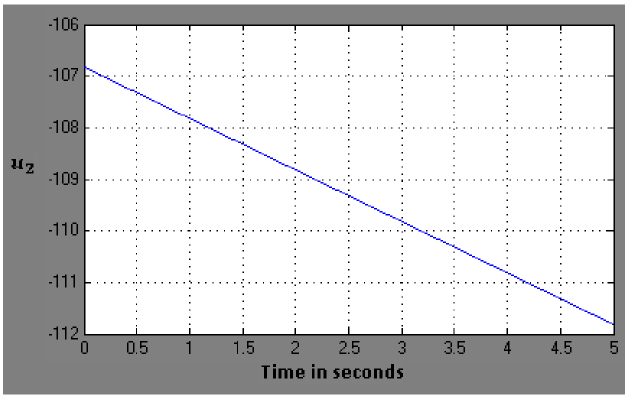

Fig.9. Estimated value of u_2

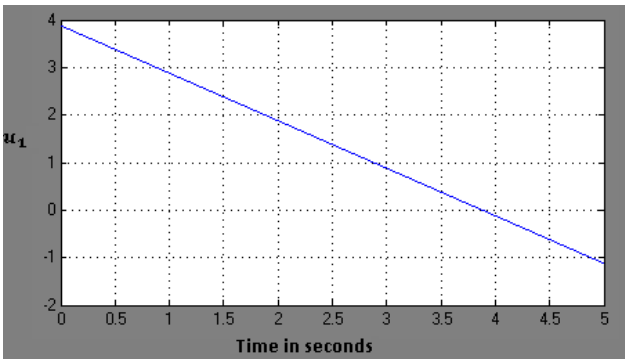

Fig.10. Estimated value of u1

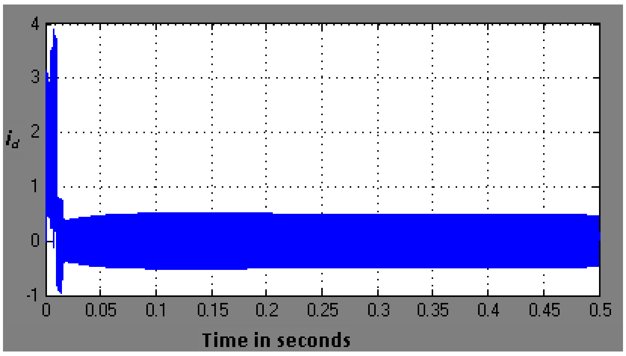

Fig.11. Actual d-axis stator current

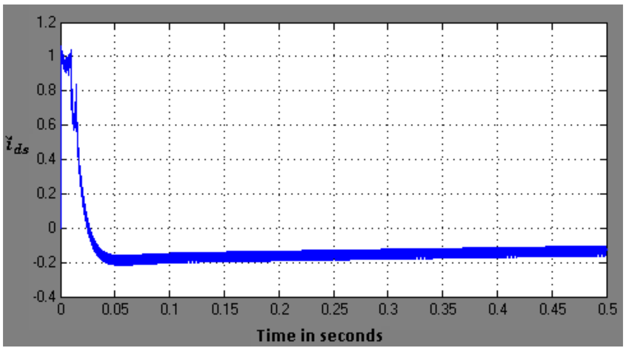

Fig.12. Estimated value of d-axis current

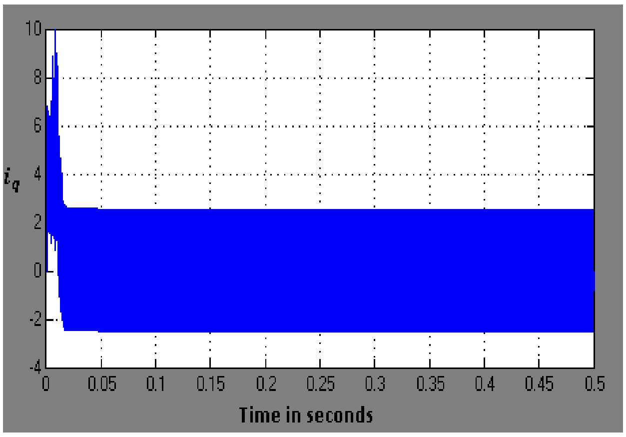

Fig.13. Actual q-axis stator current

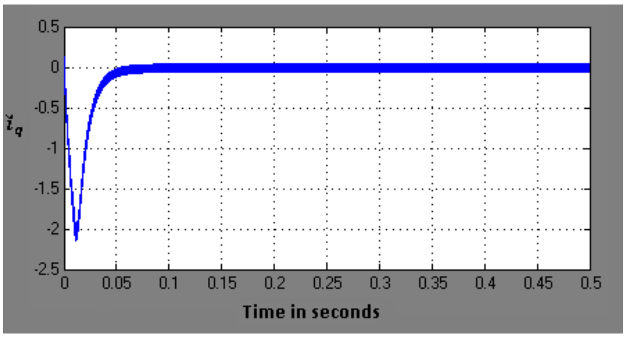

Fig.14. Estimated value of q-axis current

5 Conclusion

A new algorithm using the sliding mode control technique for induction motor parameters rotor and stator resistance estimation and compensation is proposed in this paper. The simulation done in Matlab/Simulink, the result shows the effectiveness of the proposed method. The suggested algorithm provides high dynamic response as the result analysis the system reach the sliding surface within 0.1 seconds and maintain their even the variation in resistances this shows the robustness of the method and the control signals u_1 and u_2 estimate as well as compensate R_1 and R_2 within 5 seconds that makes it better than another method of parameter compensation in induction motor. In the proposed algorithm assumed that the inductance is constant even the inductance also vary when the motor operates, in future the estimation and compensation of inductance also included in the proposed algorithm.

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