An Adaptive Neuro Fuzzy based SMO for Speed Estimation of Sensorless Induction Motor Drives at Zero and Very Low Speeds

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Abstract - *An effective speed control of sensorless induction motor (IM) drives at zero and very low speeds is achieved through the model reference adaptive system (MRAS). The stator current, rotor flux, and rotor speed is estimated by proposed adaptive sliding mode observer (SMO). An adaptive SMO is to enhance the robustness, accuracy and effective speed tracking between actual and estimated speed during very low speed operation.*

The indirect field oriented control (IFOC) for speed control of a sensorless IM drive using the proposed estimation algorithms evaluated in MATLAB/Simulink environment. The simulation studies carried out by proposed control strategies to achieve the accuracy and robustness. Comparative analysis carried out with the state of the art methods produced better transient and steady-state speed estimation. In this paper, PI controller and Adaptive Neuro Fuzzy logic controller is used to estimate the speed of the IM drive.

Key Words: **Induction motors, Sensorless control, Adaptive SMO gains, IFOC, SMO, Adaptive Neuro Fuzzy Inference System (ANFIS), MRAS.**

1. INTRODUCTION

Induction motors (IMs) are attracted by characteristics like robustness, ruggedness, simple construction, low cost, and less maintenance. Vector control theory has enhanced the dynamic performance of IM drives as like in the separately excited DC motors.IM drives require precise control such as actuation, robotics, and numerically controlled machinery. For field orientation, the exact knowledge of rotor position signal is required. Also, for closed-loop control requires the precise speed signal so that position encoders are supposed to be placed on the rotor shaft for the exact position and speed. But it causes extra cost, heavy size, and large wiring of IM drives and mitigates their applications in a harsh environment.

In present, without position encoders have becoming huge popular due to their advantages of lessen production cost, reliable and robust control system.

The present trend in research work on replacing the position encoder to make sensorless drives without destroying their dynamic performance. Various position and speed estimation methods of the sensorless drives have been proposed. These are classified as machine model-based and high-frequency signal injection methods [2]-[4].

The high-frequency signal injection machine model independent schemes are shows insensitive to parameters variation that accurate speed and position estimation, particularly at very low and zero speeds. Due to high-frequency noise system performance degradation occurs; moreover require a specific design [4].

At high and medium speeds, the accurate and robust speed estimation possible by employing Machine model-based schemes. For very low speed operation continues to be researched to increase their reliability in this operating region [2]-[3]. The literature studies have been thoroughly on MRAS observers, Sliding mode observer (SMO) and adaptive flux observer (AFO). SMO, as variable structure control is highly recommending for MRAS speed-estimation methods based on SMO to enhance the estimation accuracy.

The main essential work of this paper is, comparative analysis is done between conventional PI controller and proposed ANFIS controller and proves the accuracy and robustness of the system enhances with measuring various quantities like speed, speed error, load currents and stator currents in reference frame to validate the effectiveness of the control and proposed estimation.

2. MODEL REFERENCE ADAPTIVE SYSTEM

MRAS method is based on rotor flux of the machine and uses two model known as reference and adaptive model. The obtained fluxes from the mentioned models are compared to produce an error signal to estimate the speed.

Reference model: Speed independent model; build from the stator equations,

$$\begin{cases} \frac{d}{dt}\phi_{rd} = \frac{L_r}{L_m} v_{sd} - \sigma L_s \frac{d}{dt} i_{sd} - R_s i_{sd} \\ \frac{d}{dt}\phi_{rq} = \frac{L_r}{L_m} v_{sq} - \sigma L_s \frac{d}{dt} i_{sq} - R_s i_{sq} \end{cases}$$

Adaptive model: Speed dependent model; build from the rotor equations,

$$\begin{cases} \frac{d}{dt}\hat{\phi}_{rd} = \frac{L_m}{\tau_r} i_{sd} - \frac{1}{\tau_r}\hat{\phi}_{rd} + (\omega_s - p\Omega_{est})\hat{\phi}_{rq} \\ \frac{d}{dt}\hat{\phi}_{rq} = \frac{L_m}{\tau_r} i_{sq} - (\omega_s - p\Omega_{est})(\hat{\phi}_{rd} - \frac{1}{\tau_r}\hat{\phi}_{rq}) \end{cases}$$

The estimator stability

$$\varepsilon = \phi_{rq}\hat{\phi}_{rd} - \phi_{rd}\hat{\phi}_{rq}$$

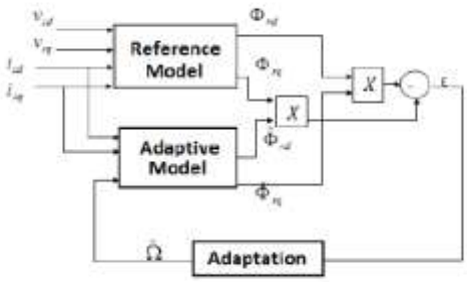

Fig-1: MRAS Observer Strategy

Speed estimation expression is given by

$$\hat{\Omega} = K_p\varepsilon + \int K_i \varepsilon dt$$

K_p and K_i are positive gains.

Conventionally utilizes a PI controller. When the error between the two models is not zero then the adaptation mechanism tunes the rotor speed.

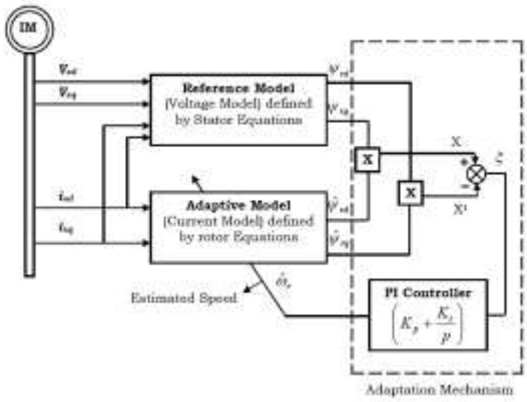

Fig-2: Block diagram of speed estimation using MRAS

3. SLIDING MODE OBSERVER

The present trend of using SMO to estimate the speed of IM drives where it is based on Variable Structure Control (VSC) theory provides better performance against dynamics, insensitivity to change in parameters, external disturbance rejection and faster dynamic response. It is a great deal to mitigate the chattering effect in IM drives.

Dynamic model of IM in the stationary reference frame having stator current and rotor flux,

$$\frac{d}{dt}\begin{bmatrix} i_s^s \\ \lambda_r^s \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}\begin{bmatrix} i_s^s \\ \lambda_r^s \end{bmatrix} + \begin{bmatrix} b_1 \\ 0 \end{bmatrix}\begin{bmatrix} u_s^s \end{bmatrix} = Ax + Bu_s$$

Where

$$a_{11} = aI,\quad a_{12} = cI + dJ,\quad a_{21} = eI,\quad a_{22} = -\varepsilon a_{12},\quad b_1 = bI$$

$$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix},\quad J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

To estimate the rotor flux from SMO,

$$\frac{d\hat{x}}{dt} = \hat{A}\hat{x} + Bu_s + K_1 \operatorname{sgn}\left(\hat{i}_s^s - i_s^s\right)$$

Where $\mathbf{K_1}$ is a gain matrix

$$K_1 = [K \ \ {-K}]^T,\ K = kI$$

k is the switching gain.

Rotor speed estimation based on Lyapunov theory:

$$\hat{\omega}_r = -k\int\left[\operatorname{sgn}\left(\hat{i}_{ds}^s - i_{ds}^s\right)\cdot\hat{\lambda}_{qr}^s - \operatorname{sgn}\left(\hat{i}_{qs}^s - i_{qs}^s\right)\cdot\hat{\lambda}_{dr}^s\right]dt$$

Where,

$$a = -\left(\frac{R_s}{\sigma L_s} + \frac{L_m^2}{\sigma L_s T_r L_r}\right),\quad c = \frac{1}{\varepsilon T_r},\quad d = \frac{\omega_r}{\varepsilon},\quad e = \frac{L_m}{T_r}$$

$$\varepsilon = \frac{\sigma L_s L_r}{L_m},\quad b = \frac{1}{\sigma L_s},\quad \sigma = 1 - \frac{L_m^2}{L_s L_r},\quad T_r = \frac{L_r}{R_r}$$

$$A_{11} = -\left(\frac{R_s}{\sigma L_s} I + \omega_r J\right),\ A_{12} = R_r\frac{(1-\sigma)}{\sigma L_m} I,\ A_{21} = R_r\frac{(1-\sigma)}{\sigma L_m} I,$$

$$A_{22} = \frac{-R_r}{\sigma L_r} I,\ B_1 = I,\ C = \begin{bmatrix} \frac{1}{\sigma L_s} I & \frac{\sigma - 1}{\sigma L_m} I \end{bmatrix}$$

The structure of the sliding mode speed estimation algorithm is shown in Fig.3.

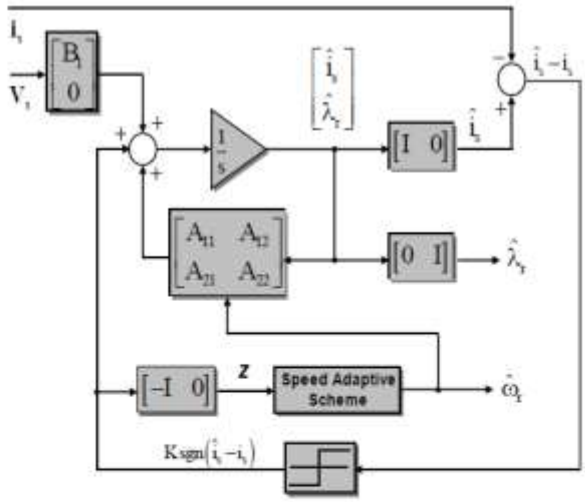

Fig-3: Block diagram of SMO

A **second-order** sliding mode observer design is used to minimize the filtering.

3.1 Sliding Mode Observer for Fluxes and Speed (Adjustable model)

The rotor equations are used in designing the adjustable model, this observer estimates both the fluxes and the speed.

$$\frac{d\lambda_\alpha}{dt} = -\eta\hat{\lambda}_\alpha - n_p\hat{\omega}_r\hat{\lambda}_\beta + \eta L_m i_\alpha$$

$$\frac{d\lambda_\beta}{dt} = n_p\hat{\omega}_r\hat{\lambda}_\alpha - \eta\hat{\lambda}_\beta + \eta L_m i_\beta$$

$$\hat{\omega}_r = M\cdot \text{sign}(s)$$

$$s = \hat{\lambda}_\alpha\lambda_\beta - \hat{\lambda}_\beta\lambda_\alpha$$

Where, $\eta = \frac{R_r}{L_r}$

The (manifold) s is differentiated and is given by:

$$\dot{s} = n_p\omega_r\,(\hat{\lambda}_\alpha\,\lambda_\alpha + \hat{\lambda}_\beta\,\lambda_\beta) + 2\,\eta\,(\hat{\lambda}_\beta\,\lambda_\alpha - \hat{\lambda}_\alpha\,\lambda_\beta) + \eta\,L_m\,[(\hat{\lambda}_\alpha - \lambda_\alpha)\,i_\beta - (\hat{\lambda}_\beta - \lambda_\beta)\,i_\alpha] - n_p(\hat{\lambda}_\alpha\lambda_\alpha + \hat{\lambda}_\beta\lambda_\beta)\,\hat{\omega}_r$$

The manifold tends to zero and sliding mode occurs..

$$\omega_{r,eq} = \omega_r + \frac{\eta\,L_m\,[(\hat{\lambda}_\alpha - \lambda_\alpha)i_\beta - (\hat{\lambda}_\beta - \lambda_\beta)i_\alpha] + 2\,\eta\,(\hat{\lambda}_\beta\,\lambda_\alpha - \hat{\lambda}_\alpha\,\lambda_\beta)}{\hat{\lambda}_\alpha\,\lambda_\alpha + \hat{\lambda}_\beta\,\lambda_\beta}$$

If the adjustable model converges and the switching term is redesigned as:

$$\hat{\omega}_r = \alpha\sqrt{|s|}\text{sign}(s) + \beta\int(\text{sign}\ (s))$$

Where, α and β are constant design parameters (positive).

4. ANFIS CONTROLLER

ANFIS controller having hybrid features of FIS system and the artificial neural networks. In FLC, the fuzzy rules output is tuned automatically by ANN methods that is least square recursive method with back propagation algorithm.

In this paper, we proposed two inputs with 7 fuzzified values in fuzzy controller system having 49 fuzzy rules are framed. By using Neural Network back propagation, corresponding Rules are trained and then selected, where the speed is output. The output speed is,

$$y = \frac{\sum_{i=1}^{R}\mu^i a_1^i x_1 + \wedge + \sum_{i=1}^{R}\mu^i a_q^i x_q}{\sum_{i=1}^{R}\mu^i}$$

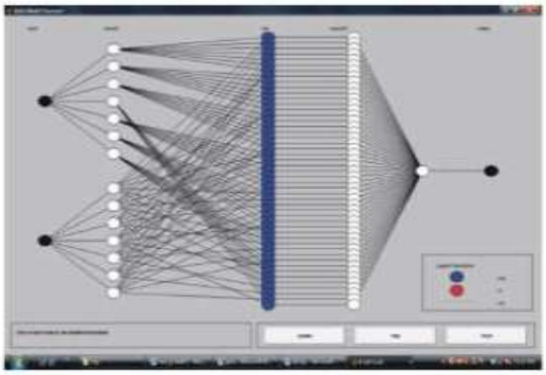

Fig-4: ANN structure with two inputs for ANFIS controller.

Table -1: ANFIS rule base for speed

E / ΔE	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

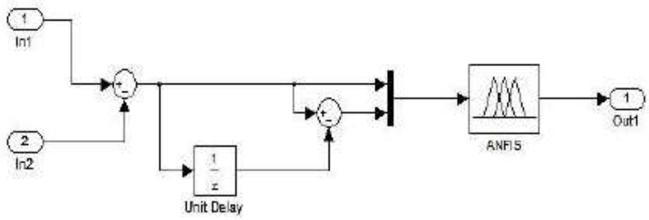

Fig-5: ANFIS controller in proposed system Rules are fired and one output by system

5. SIMULATION RESULTS

5.1 WITH PI CONTROLLER

5.1.1 Performance at Zero Speed

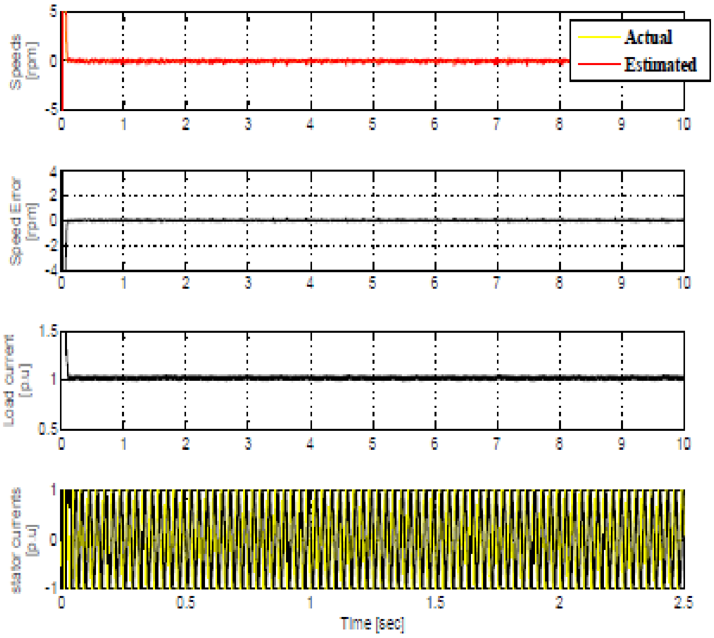

Fig -6: Simulation results of sensorless speed control with rated load torque at zero speed.

5.1.2. Performance at Zero and Very low Speeds under Sudden Load Disturbances

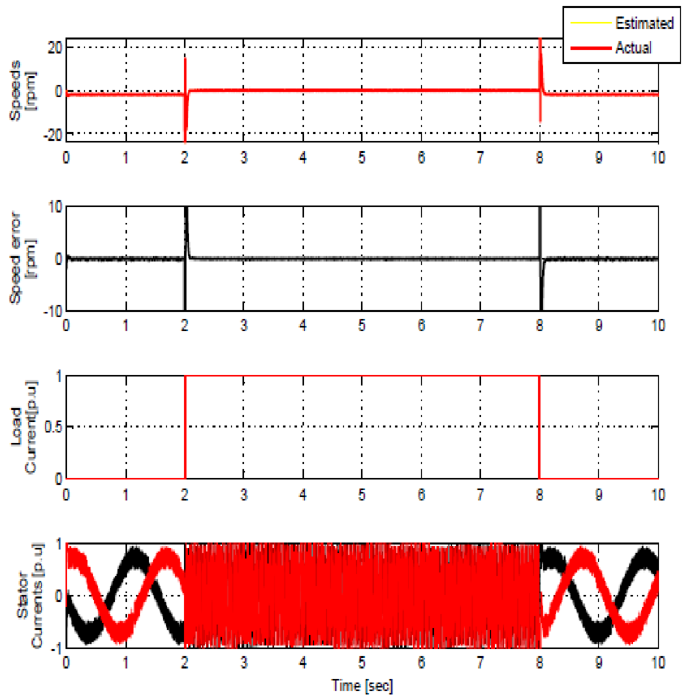

Fig -7: Simulation results of sensorless speed control with Load change ($T_L = 0$) at zero speed.

5.1.3 Performance under Step Speed Change and Speed Reversal

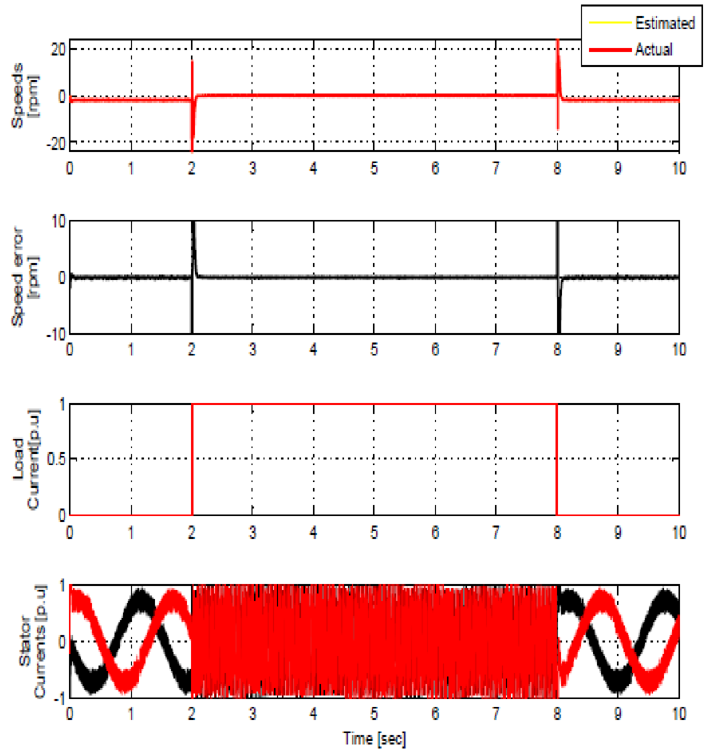

Fig-8: Simulation results of sensorless speed control with load change (TL = 0 ➔ rated torque ➔ 0) at very low speed of 2 rpm.

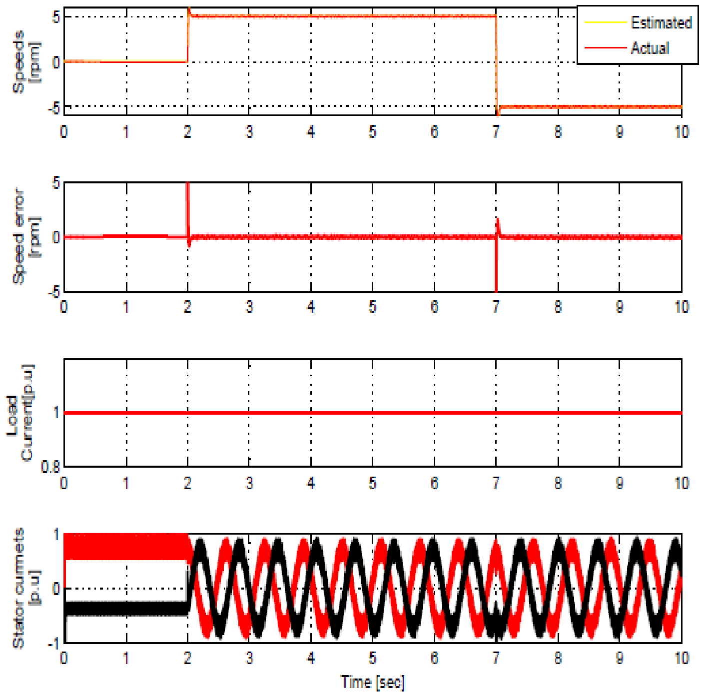

Fig.-9: Simulation results of sensorless speed control with rated load torque at step speed change and speed reversal at 5 rpm.

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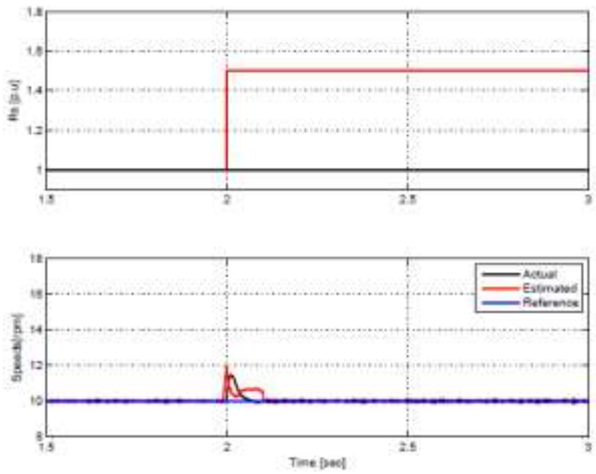
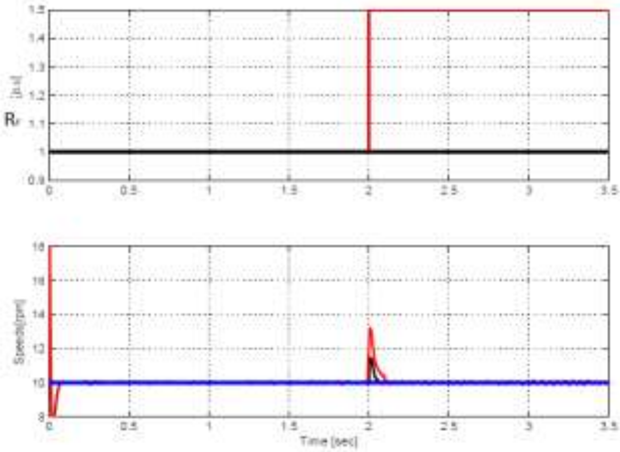
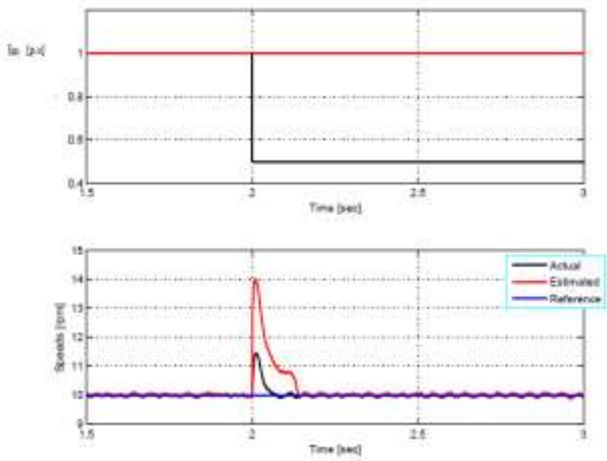
5.1.4 PARAMETER SENSITIVITY



(a)



(b)



(c)

Fig- 10: Simulation results showing the performance of the proposed SMO under the effect of parameters variation during low speed of 10 rpm and rated load torque. (a) 50% step change of stator resistance. (b) 50% step change of rotor resistance. (c) 50% step change of mutual inductance.

5.2 WITH ANFIS CONTROLLER

5.2.1 Performance at Zero Speed

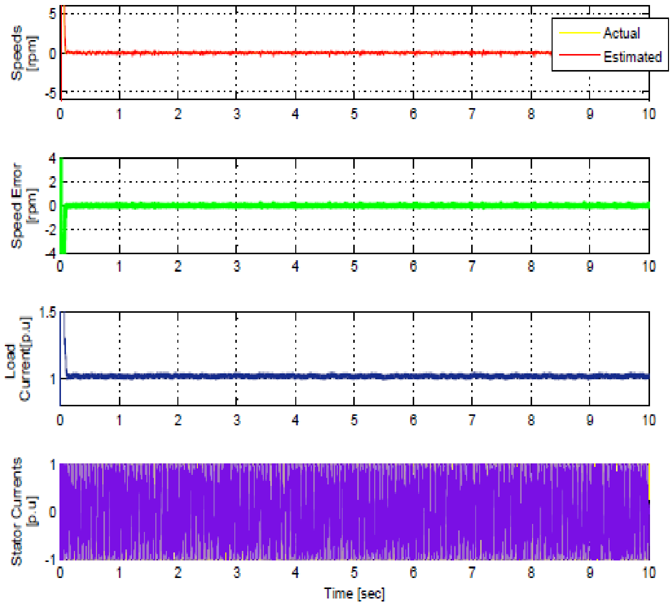


Fig-11: Simulation results of sensorless speed control with Rated load torque at zero speed.

5.2.2. Performance at Zero and Very low Speeds under Sudden Load Disturbances

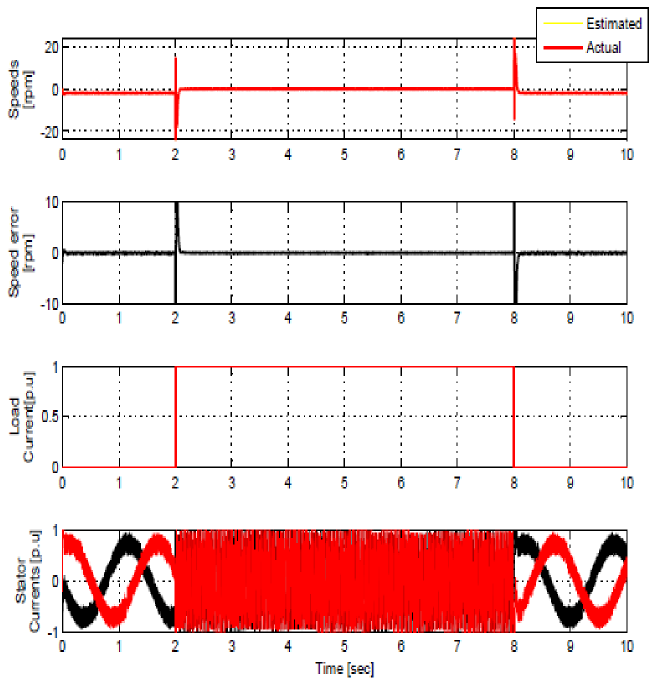


Fig -12: Simulation results of sensorless speed control with load change ($T_L = 0$) at zero speed.

5.2.3 Performance under Step Speed Change and Speed Reversal

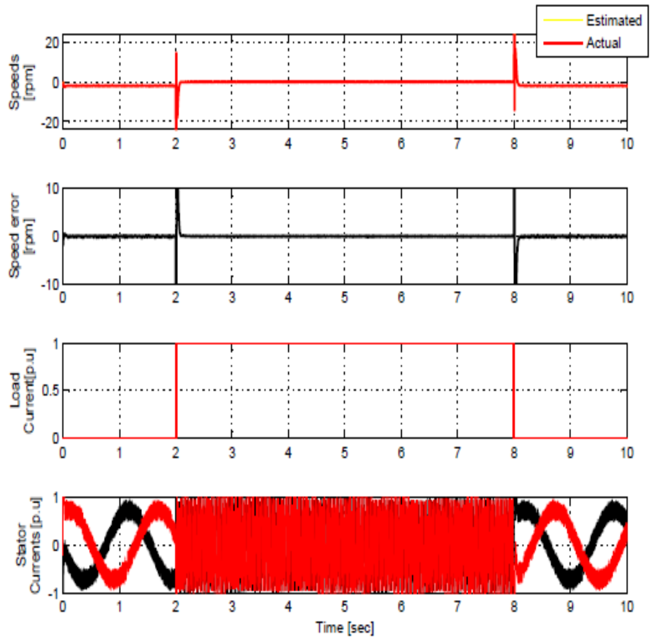


Fig-13: Simulation results of sensorless speed control with load change ($T_L = 0$) at very low speed of 2 rpm

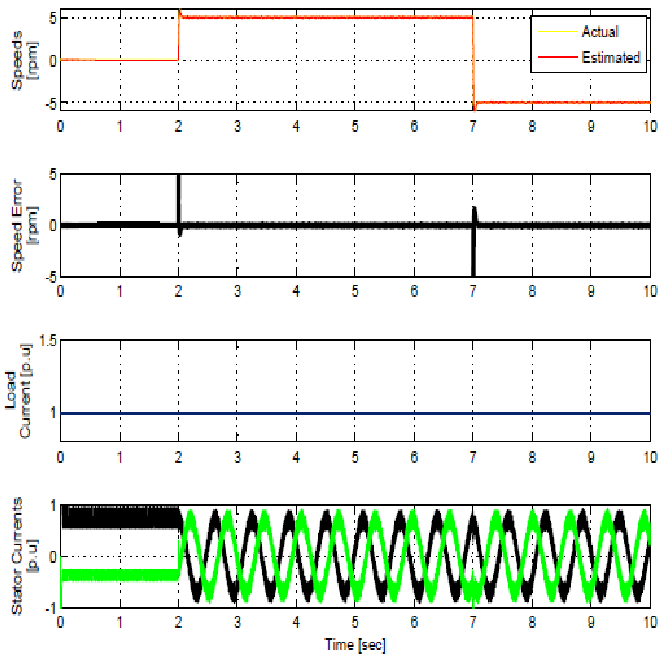
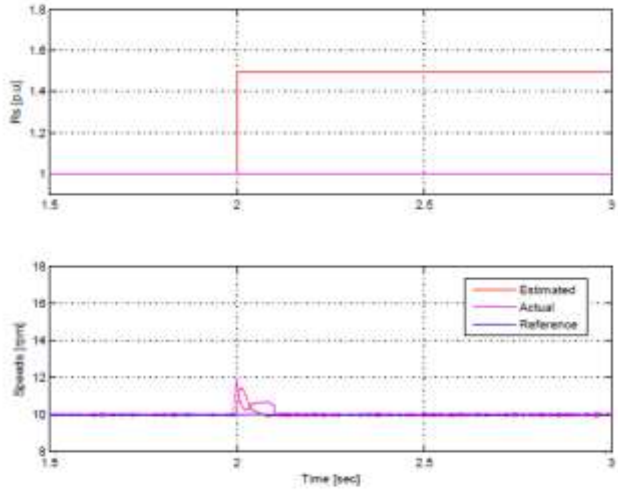
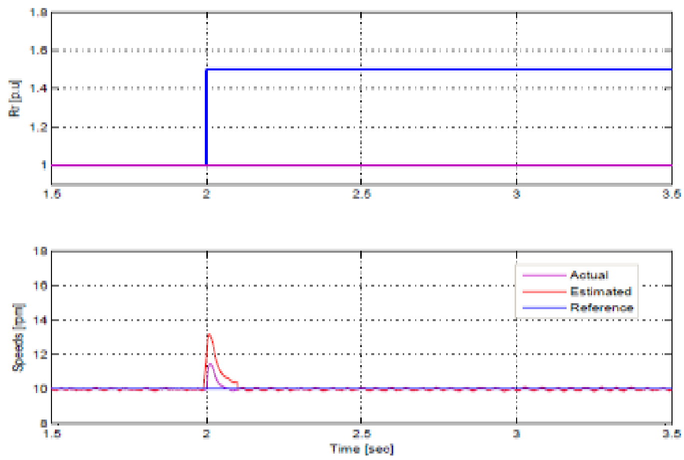


Fig -14: Simulation results of sensorless speed control with rated load torque at step speed change and speed reversal at 5 rpm.

5.2.4 PARAMETER SENSITIVITY



(a)



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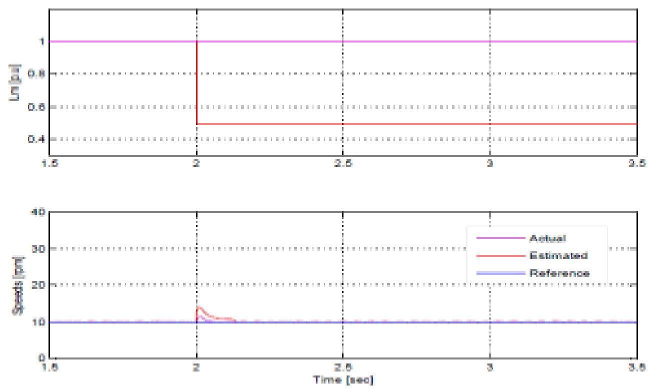
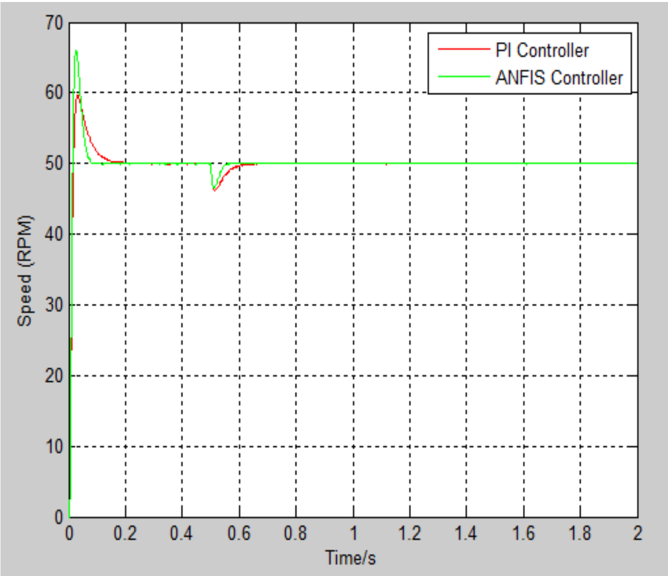
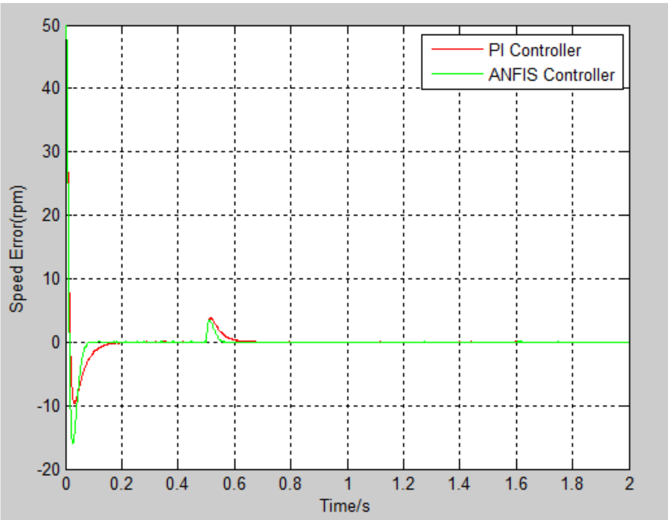


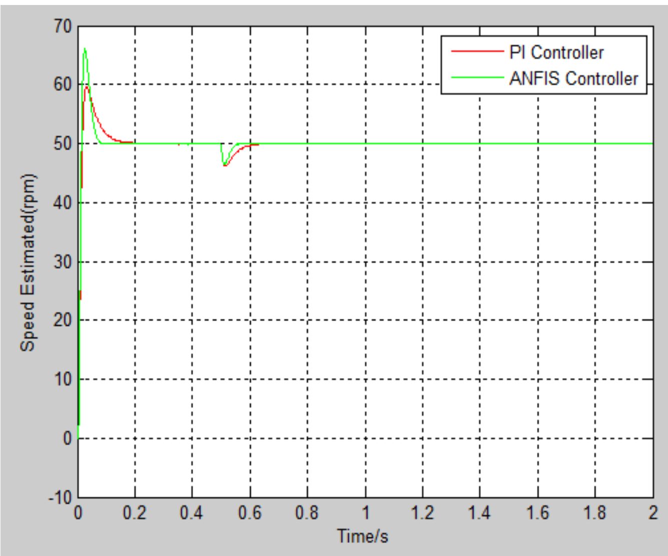
(c)

Fig -15: Simulation results showing the performance of the proposed SMO under the effect of parameters variation during low speed of 10 rpm and rated load torque. (a) 50% step change of stator resistance. (b) 50% step change of rotor resistance. (c) 50% step change of mutual inductance.

6. COMPARISON RESULTS







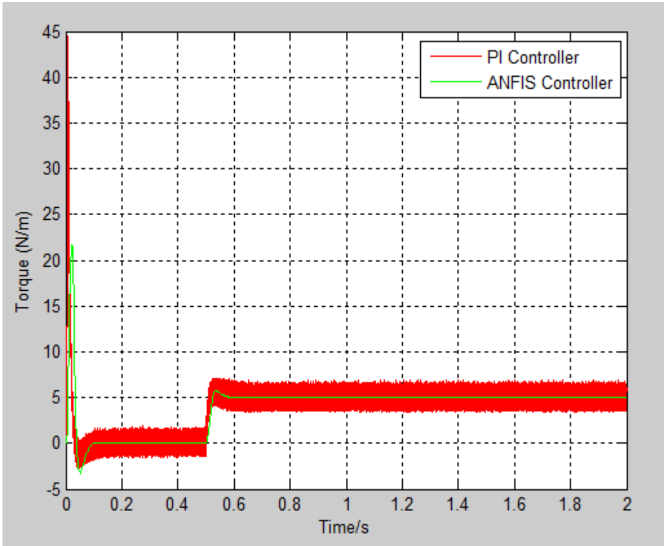


Fig -16: comparison between existed and proposed methods of various parameters

Table -2: Comparison between PI and ANFIS Controller in Settling Time (seconds)

PARAMETER	PI CONTROLLER	ANFIS CONTROLLER
Speed (50 rpm)	0.6	0.5
Speed Error (ZERO rpm)	0.7	0.5
Estimated Speed (49.5 rpm)	0.6	0.5

7. CONCLUSION

In this paper, Simulation results confirm the effectiveness of the SMO for estimating rotor speed of the IM at very low and zero speeds with the conventional PI and ANFIS controllers. It has been found that the estimation accuracy of rotor speed is better at different operating conditions. Moreover, estimation error decays rapidly, closer to zero after the application and removal of load torque. This shows that the estimated speed tracking is quite good enough in all conditions especially at transient state. Stability and robustness of the machine is also enhanced with ANFIS Controller compare to PI controller by observing settling time. The estimated speed tracks the actual one with a good convergence. As obvious, these results confirm the effectiveness of the proposed SMO under parameters variation. The simulation results showing that the proposed method is parameter insensitive and able to track the slow variations of actual machine parameters.

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