AN ADAPTIVE SPEED SENSORLESS INDIRECT VECTOR CONTROL OF AN INDUCTION MOTOR DRIVE WITH FUZZY LOGIC CONTROLLER

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Abstract: *A novel Fuzzy logic based adaptation mechanism is proposed to replace the conventional PI controller used in the rotor flux based model reference adaptive system (MRAS). Such adaptive system works satisfactorily in all four quadrants of operation. A detailed comparison between the classical and new schemes is done in closed loop sensorless mode of operation. Computer simulation study is carried out in MATLAB/SIMULINK environment. Superior dynamic performance is observed using proposed Fuzzy logic controller based speed estimator. Prototype experimentation using TMS 320F28335 DSP controller in the Laboratory confirms superior performance of the proposed controller.*

Key words: *induction motor (IM), model reference adaptive system (MRAS), sensorless, indirect vector control, Fuzzy logic*

LIST OF SYMBOLS

v_{sD},v_{sQ} Stator voltage components in the stator frame.

i_{sD},i_{sQ} Stator current components in the stator frame.

ψ_{rd}, ψ_{rq} Components of the rotor flux linkage vector.

T_r	Rotor time constant.
L_m	Mutual inductance.
L_r	Self-inductance at the rotor side.
L_s	Self-inductance at the stator side.
σ	Total leakage factor.
$\widehat{\omega}_r$	Estimated rotor speed.
ω_r	Rotor speed.
R_s	Stator resistance.
R_r	Rotor resistance.
p	Differential operator.
$\mathcal{E}_\omega$	Speed tuning signal.

1. **Introduction**

Induction motors are widely used in most of the industrial applications due to its low cost and simple and robust construction. The vector controlled induction motor drive is most common in industries due to fast response in speed and torque [1]-[3].But rotor speed information is required in the indirect vector control implementation. Mounting, Signal transmission and Hazardous Environment etc. are the problems associated with the use of speed sensor. So speed estimation from machine terminal quantities (voltages and currents) is preferred [2].The speed sensorless techniques are several and they are classified based on full order and reduced order observers, sliding modes, artificial neural network, kalman filter, predictive control, signal injection and model reference adaptive system[4],[5],[14]-[18].

MRAS is the most common strategy due to its simplicity and low computational effort. MRAS is classified in to following types 1.Flux based MRAS 2.Back EMF based MRAS and 3.Reactive power based MRAS [5]. The back EMF based MRAS scheme have stability problem at low stator frequency but avoids pure integration. The reactive power method has robustness but suffers from instability. Hence rotor flux MRAS proposed by Schauder is the popular strategy [13]. But it has a disadvantage that the model-based speed estimation technique fails at zero speed because rotor induced voltages are very small or zero [14]. Fuzzy logic controller performs well in low speed region. It is stable in all four quadrants of operation. In a conventional mathematical based MRAS, the reference model quantities are compared with state variables estimated using an adaptive model. The difference between these variables is then used in an adaptation mechanism. The output of adaptation mechanism is the estimated rotor speed which adjusts the adaptive model until satisfactory performance is obtained [5].The PI controller is the conventionally used controller since its synthesis is based on simple and well known automatic control methods. But unmodelled dynamics (filters, sensors and inertia inverter) the eventual mistakes on the moment of

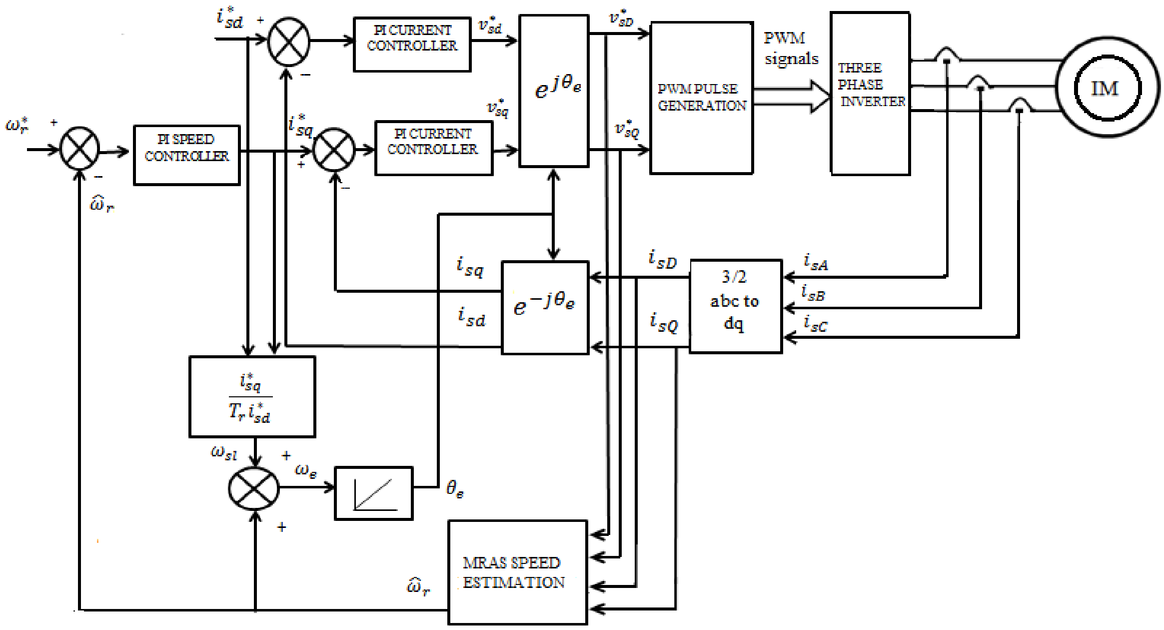


Fig.1. Sensorless indirect vector controlled induction motor drive with MRAS speed estimation

Inertia value and nonlinearity in the electromagnetic torque make PI controller unable to perform well [14]. To overcome above problems, Fuzzy logic controllers have been proposed. It found more suitable for high performance industrial drive applications [17]. In [23], a dead beat direct torque controller is developed for induction motor drive. Paper [24] has discussed about the perspectives of observer theory in induction motor to test the problem of flux estimation. For the standard induction motor, a closed loop flux observer is designed in [25]. In [26], modified direct torque controller with space vector modulation (DTC-SVM) is discussed to improve the overall performance of the induction motor drive. Fuzzy logic is used to update rotor resistance value in indirect field oriented control of induction motor [27]. In [28], sliding mode MRAS is proposed for Sensorless induction motor drive. Neural network and fuzzy logic controllers are used for the rotor and stator resistance estimations [29]. In [30], PI and fuzzy logic controllers are used to tune stator resistance in DTC method.

In this work an adaptive fuzzy controller is used to solve speed estimation problem. In induction motor, speed estimation is considered as an optimization problem. Since we are concentrating on the low speed operation, effects of magnetic saturation and rotor temperature on the performance of the drive are not included. A detailed simulation and experimental study is presented with MATLAB/SIMULINK environment. In this present work, comparison between Fuzzy and PI controller is carried out. Superior performance of the proposed Fuzzy controller is observed both in experimental and simulation results.

2. Rotor Flux MRAS Speed Observer

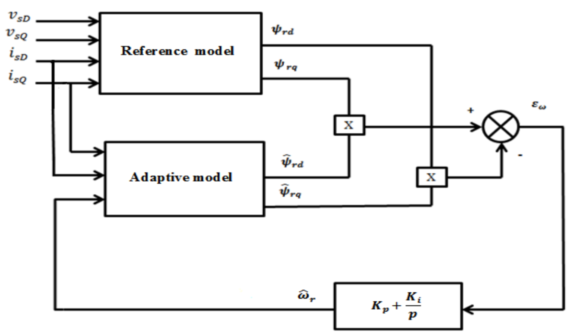


Fig.2.Block diagram of conventional MRAS

Fig.1. shows the basic structure of indirect vector control for sensorless induction motor drive, in which MRAS is used to estimate induction motor speed. Fig.2. shows the block diagram of conventional

MRAS. It consists of reference model, adjustable adaptive model and an adaptation mechanism. Voltage model's equations represents reference model. In this model rotor flux components are expressed in terms of stator voltage and current components. Current model Equations represents adaptive model. In this model, rotor flux components are expressed in terms of rotor speed and stator current components. Stator voltage equations in stationary reference frame are written as

$$v_{sD} = R_s i_{sD} + \sigma L_s p i_{sD} + \frac{L_m}{L_r} p\psi_{rd} \tag{1}$$

$$v_{sQ} = R_s i_{sQ} + \sigma L_s p i_{sQ} + \frac{L_m}{L_r} p\psi_{rq} \tag{2}$$

Rearranging equations (1) and (2) we get

$$p\psi_{rd} = \frac{L_r}{L_m}\{v_{sD} - R_s i_{sD} - \sigma L_s p i_{sD}\} \tag{3}$$

$$p\psi_{rq} = \frac{L_r}{L_m}\{v_{sQ} - R_s i_{sQ} - \sigma L_s p i_{sQ}\} \tag{4}$$

Equations (3) and (4) represent the reference model. The rotor voltage equations represented in stationary reference frame are

$$0 = \frac{1}{T_r}\psi_{rd} - \frac{L_m}{T_r} i_{sD} + p\psi_{rd} + \omega_r \psi_{rq} \tag{5}$$

$$0 = \frac{1}{T_r}\psi_{rq} - \frac{L_m}{T_r} i_{sQ} + p\psi_{rq} - \omega_r \psi_{rd} \tag{6}$$

Rearranging the (5) and (6) equations we get

$$p\psi_{rd} = \frac{L_m}{T_r} i_{sD} - \frac{1}{T_r}\psi_{rd} - \omega_r \psi_{rq} \tag{7}$$

$$p\psi_{rq} = \frac{L_m}{T_r} i_{sQ} - \frac{1}{T_r}\psi_{rq} + \omega_r \psi_{rd} \tag{8}$$

The adaptive model equations are given by

$$p\hat{\psi}_{rd} = \frac{L_m}{T_r} i_{sD} - \frac{1}{T_r}\hat{\psi}_{rd} - \hat{\omega}_r \hat{\psi}_{rq} \tag{9}$$

$$p\hat{\psi}_{rq} = \frac{L_m}{T_r} i_{sQ} - \frac{1}{T_r}\hat{\psi}_{rq} + \hat{\omega}_r \hat{\psi}_{rd} \tag{10}$$

3. Design of MRAS Adaptation Mechanism

Popov's hyper stability theory is used to design adaptation mechanism. Fig.3 shows MRAS representation as a nonlinear feedback system where the transfer function matrix of the linear feed forward sub system is strictly positive real and nonlinear feedback subsystem satisfies Popov's integral inequality. The MRAS observer is transformed into an equivalent feed forward and feedback system by considering the state error equation of the system. It is obtained by subtracting the outputs of reference and adaptive models.

$$\varepsilon_d = \psi_{rd} - \hat{\psi}_{rd} \tag{11}$$

$$\varepsilon_q = \psi_{rq} - \hat{\psi}_{rq} \tag{12}$$

The error vector is defined as

$$\varepsilon = [\varepsilon_d \varepsilon_q]^T \tag{13}$$

Differentiating and substituting

$$p\varepsilon_d = p\psi_{rd} - p\hat{\psi}_{rd}$$

$$p\varepsilon_d = -\frac{1}{T_r}\varepsilon_d - \omega_r \varepsilon_q - (\omega_r - \hat{\omega}_r)\hat{\psi}_{rq} \tag{14}$$

$$p\varepsilon_q = p\psi_{rq} - p\hat{\psi}_{rq}$$

$$p\varepsilon_q = -\frac{1}{T_r}\varepsilon_q + \omega_r \varepsilon_d + (\omega_r - \hat{\omega}_r)\hat{\psi}_{rd} \tag{15}$$

Equations are written in standard matrix form

$$\begin{bmatrix} p\varepsilon_d \\ p\varepsilon_q \end{bmatrix} = \begin{bmatrix} \frac{-1}{T_r} & -\omega_r \\ \omega_r & \frac{-1}{T_r} \end{bmatrix} \begin{bmatrix} \varepsilon_d \\ \varepsilon_q \end{bmatrix} + \begin{bmatrix} -\hat{\psi}_{rq} \\ \hat{\psi}_{rd} \end{bmatrix} (\omega_r - \hat{\omega}_r) \tag{16}$$

This equation similar to the nonlinear feedback system and it can be written as

$$p\varepsilon = A\varepsilon - W \tag{17}$$

Where

$$A = \begin{bmatrix} \frac{-1}{T_r} & -\omega_r \\ \omega_r & \frac{-1}{T_r} \end{bmatrix} \qquad W = \begin{bmatrix} \hat{\psi}_{rq} \\ -\psi_{rd} \end{bmatrix} (\omega_r - \hat{\omega}_r) \tag{18}$$

An adaptation law is defined as [6]

$$\hat{\omega}_r = \varphi_2(\varepsilon) + \int_0^t \varphi_1(\varepsilon) d\tau \tag{19}$$

Popov's integral inequality [3] is defined as

$$\int_0^t \varepsilon^T \boldsymbol{W} dt \geq -\gamma_0^2 \tag{20}$$

Substituting equations (18) and (19) in to equation (20), we get following inequality

$$\int_0^t (\varepsilon_d \hat{\psi}_{rq} - \varepsilon_q \hat{\psi}_{rd})(\omega_r - \varphi_2(\varepsilon) - \int_0^t \varphi_1(\varepsilon) d\tau) dt \geq -\gamma_0^2 \tag{21}$$

This inequality can be satisfied using the following functions [6]

$$\varphi_1(\varepsilon) = k_2(\varepsilon_q \hat{\psi}_{rd} - \varepsilon_d \hat{\psi}_{rq}) = K_1(\psi_{rq}\hat{\psi}_{rd} - \psi_{rd}\hat{\psi}_{rq}) \tag{22}$$

$$\varphi_2(\varepsilon) = k_1(\varepsilon_q \hat{\psi}_{rd} - \varepsilon_d \hat{\psi}_{rq})$$

$$= K_p\left(\psi_{rq}\hat{\psi}_{rd} - \psi_{rd}\hat{\psi}_{rq}\right) \qquad (23)$$

Where $\varphi_2(\varepsilon)$ and $\varphi_1(\varepsilon)$are the proportional and integral parts of the adaptation law respectively.

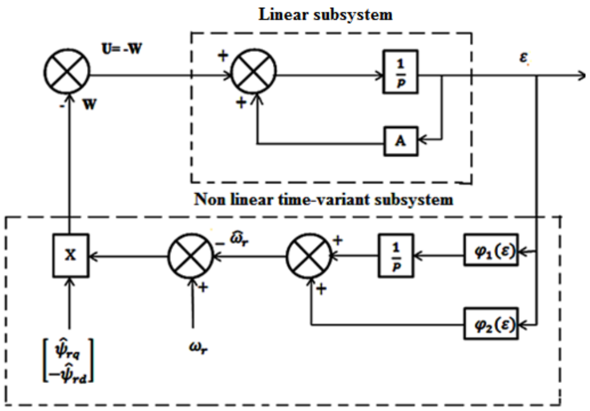


Fig.3. MRAS representation as a nonlinear feedback system [6]

The estimated speed can be defined as

$$\hat{\omega}_r = \left(k_p + \frac{k_i}{p}\right) \qquad (24)$$

where

$\mathcal{E}_\omega$ is speed tuning signal which is defined as

$$\mathcal{E}_\omega = \psi_{rq}\hat{\psi}_{rd} - \psi_{rd}\hat{\psi}_{rq} \qquad (25)$$

When $\hat{\psi}_{rd}=\psi_{rd}$ and $\hat{\psi}_{rq}=\psi_{rq}$, i.e. in steady state, the speed tuning signal reaches zero value.

4. Proposed Fuzzy Logic MRAS Speed Observer

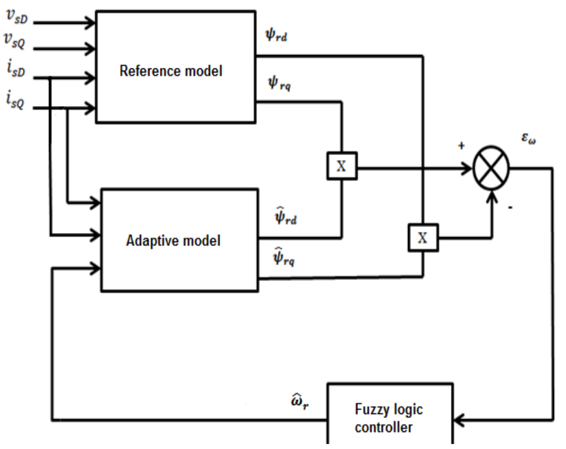


Fig.4.FLC based MRAS

Fig.4. shows block diagram of Fuzzy logic based MRAS. The most frequently used basic FL system is the Mamdani-type which consists of following parts: Fuzzification interface, Inference engine and Fuzzy rules and Defuzzification mechanism as shown in Fig.5. For induction motor drive, optimization problems are solved by FL technique. Estimation of rotor speed can be considered as an optimization problem.

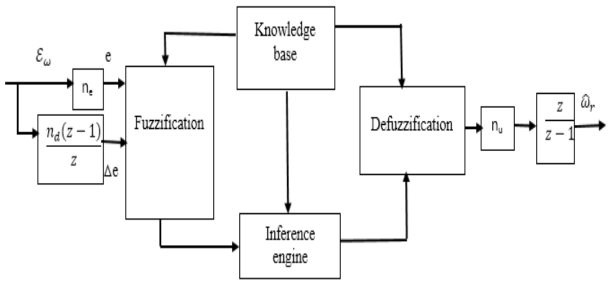


Fig.5.Fuzzy logic controller

Therefore, the conventional PI controller can be replaced by the FLC to solve the optimization problem.Fig.5. shows the block diagram of FLC. The speed error and its rate of change are the input variables. Estimated value of the speed is the ouput variable. The input /output variables used in this work are fuzzified by FIVE triangular membership functions normalized in the universe of discourse between-1 and +1. There are 25 rules used.Scaling factors n_e and n_d are multiplied with the speed tuning signal and its rate of change respectively. The controller output is multiplied with another scaling factor n_u. The discrete integration is performed finally to obtain the estimated speed . Hence the estimated speed expression can be written as

$$\hat{\omega}_r(k) = \hat{\omega}_r(k-1) + \Delta\, \hat{\omega}_r(k) \qquad (26)$$

In z domain, it is written as

$$\hat{\omega}_r(z) = \left(\frac{z}{z-1}\right) \Delta\, \hat{\omega}_r(z) \qquad (27)$$

Trial and error method is used to tune the scaling factors values. The performance of the FLC is affected by the values of scaling factors. All the variables have FIVE triangular membership functions.

Ɛω / ΔƐω	NB	NM	ZE	PM	PB
NB	NB	NB	NB	NM	ZE
NM	NB	NB	NM	ZE	PM
ZE	NB	NM	ZE	PM	PB
PM	NM	ZE	PM	PB	PB
PB	ZE	PM	PB	PB	PB

TABLE I.FUZZY Rules

The membership functions are identified as follows: NB-Negative Big, NM-Negative Medium, ZE-Zero, PM-Positive Medium, and PB-Positive Big. The computation burden of the controller is reduced by the shape of the membership functions. In this work, triangular membership function is used. The range of input and output variables varies with the change in scaling factors. Output signal is computed by the Centre of gravity method. The Table. I. shows the Fuzzy rule base 25 rules [22]. MATLAB Fuzzy-logic tool box GUI is used model the Fuzzy logic controller. Fig.6, 7 and 8 shows Membership functions, Rule viewer and Surface viewer respectively.

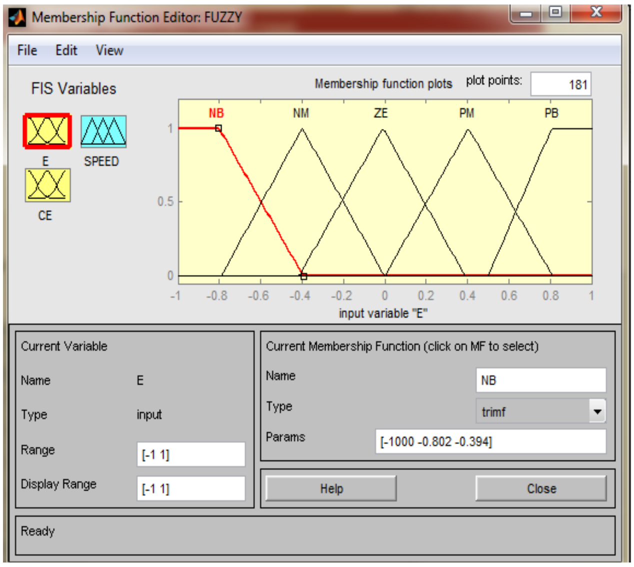


Fig.6.Memembership functions

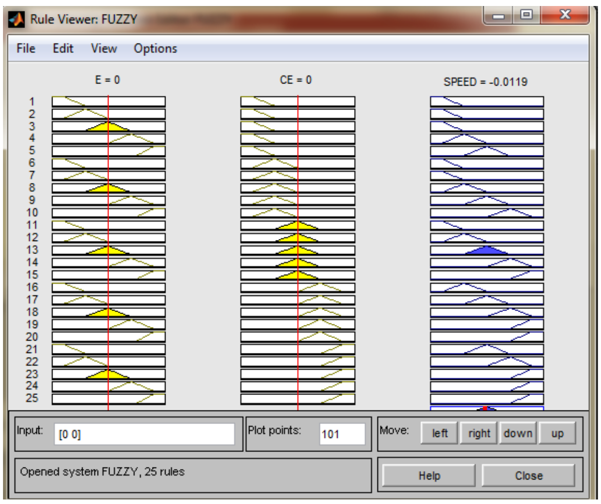


Fig.7.Fuzzy rule viewer

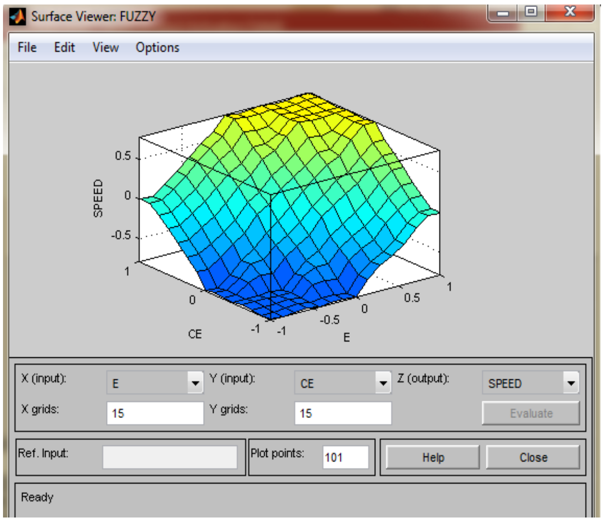


Fig.8.Surface viewer

5. Simulation Results and Discussions

The proposed Fuzzy logic and conventional PI based MRAS is simulated in MATLAB/Simulink environment and the results are presented here. The Machine parameters and ratings are presented in the Table III. The operation is tested for various operating condition like steady state and regenerative mode of operation in low speed region.

5.1. Steady State Response

The steady state response of the conventional PI and Fuzzy logic based MRAS speed estimator is shown in Fig.9. The reference speed is changed from 0 to 50 rpm. The reference and estimated speeds are shown in Fig.9. Load torque of 10 Nm is applied at 1 sec. It shows that the actual speed tracks the reference with good accuracy with Fuzzy logic controlled MRAS. The actual and estimated speeds for conventional and Fuzzy logic controller are shown in Figures 9 and10. Minimum speed estimation error is observed for Fuzzy logic controller. Speed overshoot and Torque peak overshoot are higher for conventional controller than proposed Fuzzy controller as shown in Table.II.

5.2. Dynamic Response

5.2.1. Forward and Reverse Motoring mode of Operation

Fig. 11 shows performance of conventional PI controller response in forward reverse motoring mode. The Fig.12 shows the performance of proposed Fuzzy MRAS estimator in forward and reverse motoring modes. The command speed is started from 0, changed to +50 rpm at 1 sec and then to -50 rpm at 2 sec. The actual speed tracks the reference speed with min error for Fuzzy controller.

5.2.2. Motoring and Regenerative mode of Operation.

Fig.12 shows the performance the proposed speed estimator under motoring and regenerative mode of operation. The speed command is started from 0 rpm, 50 rpm and -50 rpm. The load torque is maintained at 10 Nm. Since the load torque is maintained at positive always, positive +50rpm corresponds to motoring and negative speed -50 rpm corresponds to regenerative mode of operation. Good speed tracking is observed for Fuzzy controller. Table. II shows the comparison between conventional and proposed controller.

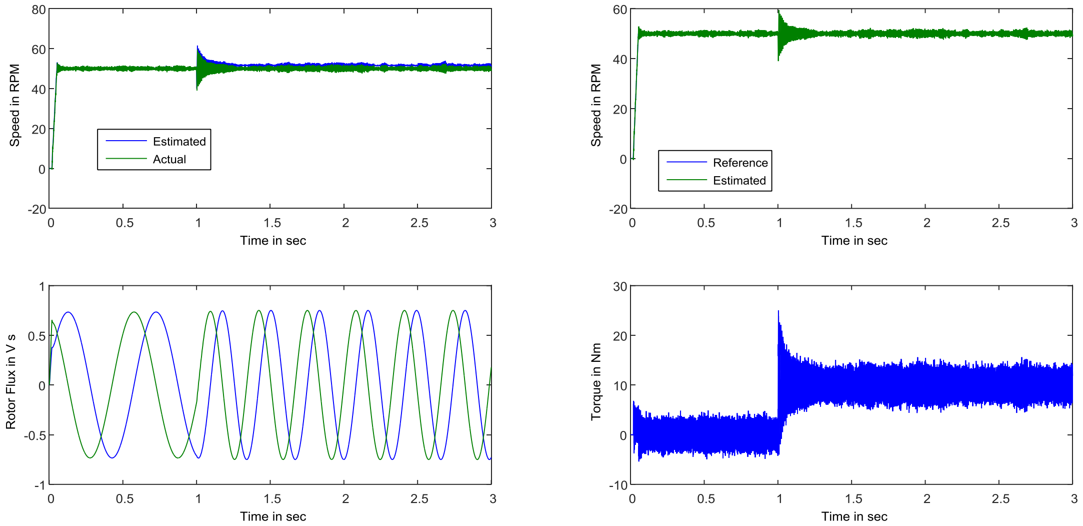


Fig.9. Steady state Response with PI controller

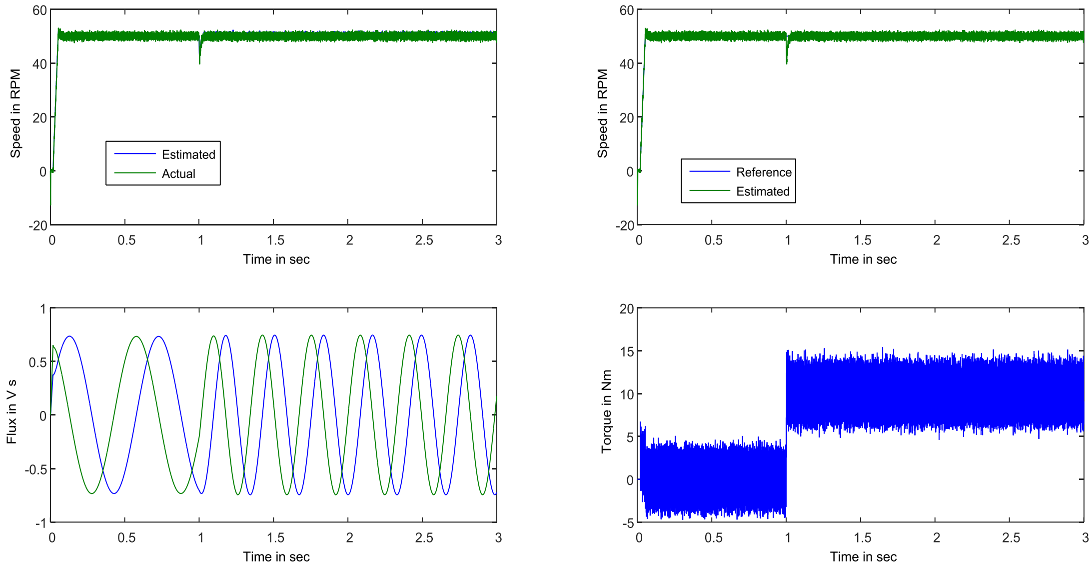


Fig. 10 Steady state Response with Fuzzy controller

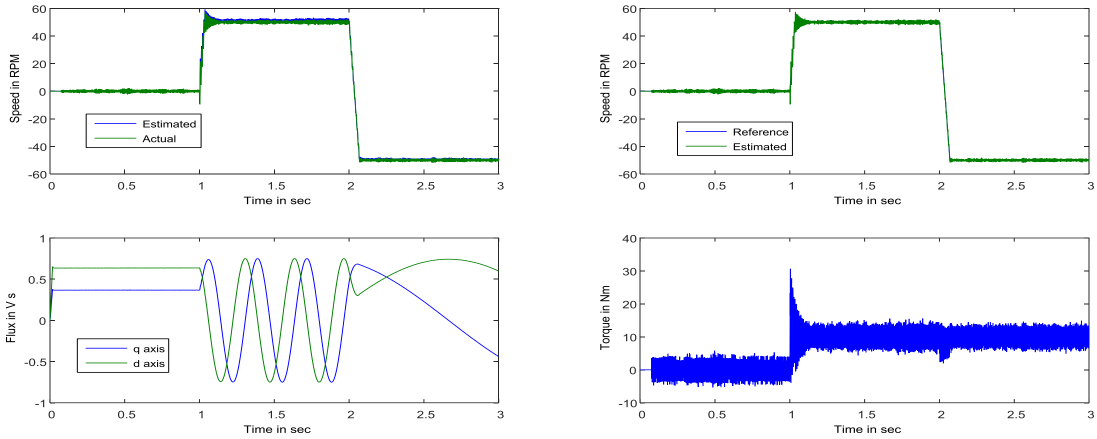


Fig.11 Dynamic Response with conventional PI controller

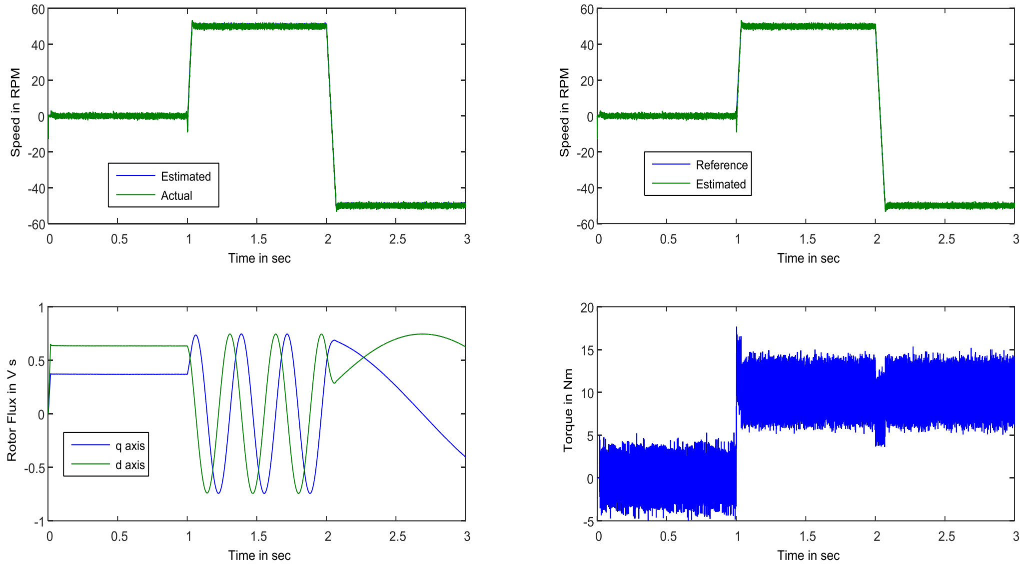


Fig. 12. Dynamic Response with Fuzzy controller

TABLE. II

COMPARISON BETWEEN CONVENTIONAL AND PROPOSED FUZZY CONTROLLER

Parameter	PI CONTROLLER		FUZZY CONTROLLER	
	Steady state Response	Dynamic Response	Steady state Response	Dynamic Response
Speed overshoot	10 RPM	8 RPM	2 RPM	1 RPM
Torque overshoot	18 Nm	23 Nm	5Nm	7Nm

6. Experimental Setup

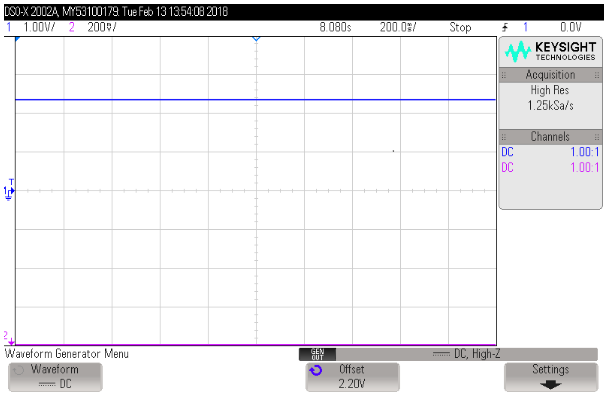
Fig.13. Hardware Setup

Fig. 13 shows the hardware implementation of the proposed Sensorless speed control of indirect vector controlled induction motor drive. TMS 320F28335 DSP controller is used for the proposed MRAS implementation.

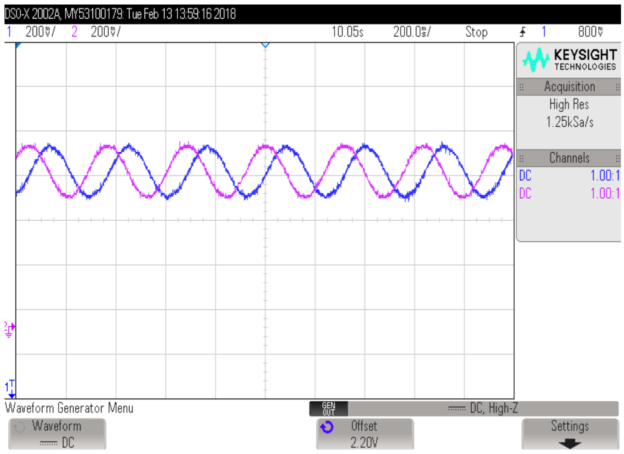
The proposed fuzzy algorithm is developed using embedded C program. The gate signals generated from the DSP controller is given to gate driver of the inverter circuit which is present in the intelligent power module (IPM). The intelligent power module consists of 1200V, 25A, 3 Phase IGBT Inverter Bridge and 1200V, 10A IGBT for over voltage breaking. Built - in over voltage, under voltage, over current & over Temperature Protection are provided in the intelligent power module. The operating speed of the DSP controller is 150 MHz. Operating voltage of the DSP controller is 1.8 V. This DSP board consists of 256 kB external RAM for program, on board isolated USB JTAG emulator,16 channel 12 bit ADC and 4 channel 12 bit DAC. Sampling speed is 12.5 MSPS (million samples per second). Conversion time is 80 ns. LV-25P and LA-25P are the voltage and current sensors used for sensing the motor voltage and currents. These values are given to the DSP controller board with the help of ADC.

7. Experimental Results

From the laboratory developed prototype as discussed in section 6, experimental results are obtained. Results are obtained through DAC which is interfaced with the DSP board.

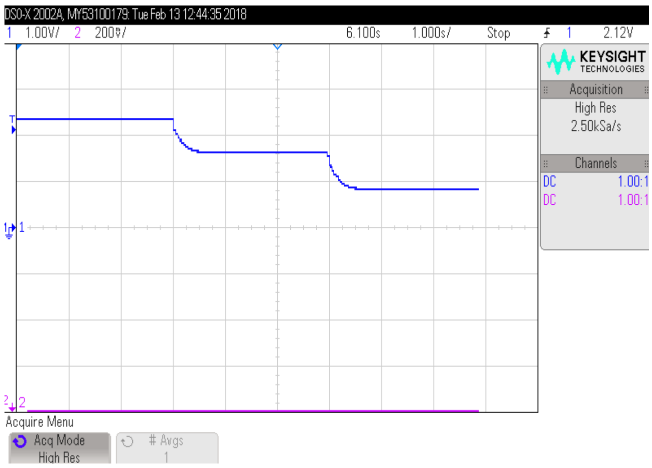


(a) Speed

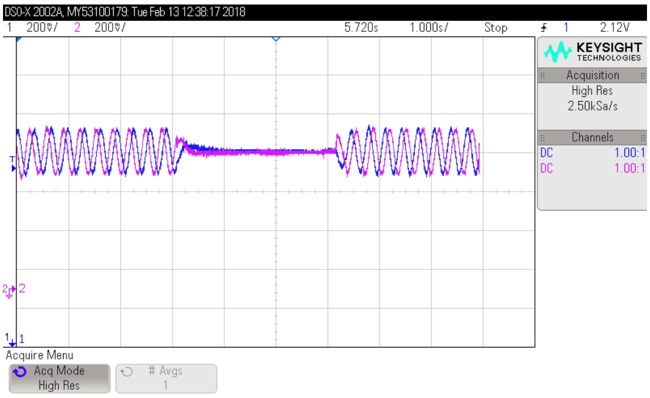


(b) Rotor fluxes

Fig. 14. Experimental Result- under steady state condition

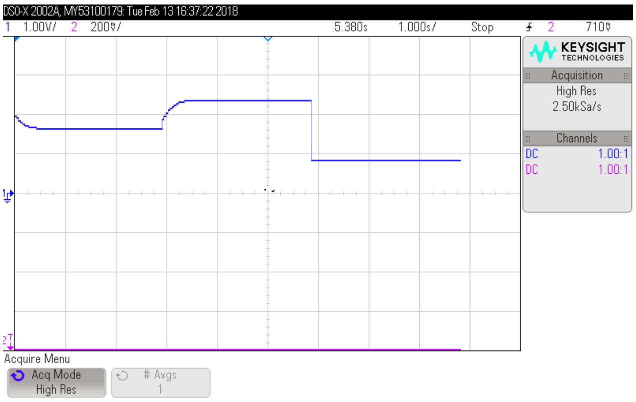


(a)Speed

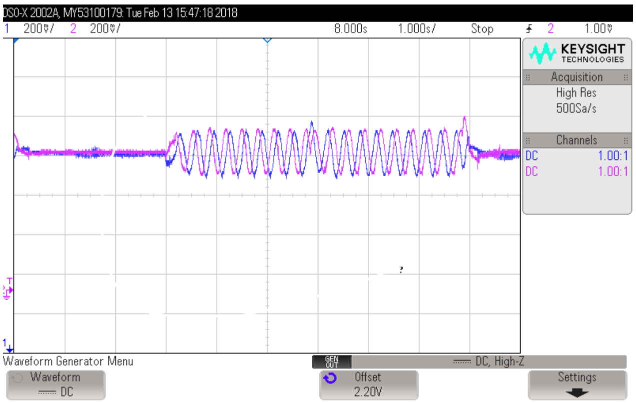


(b) Rotor Fluxes

Fig 15. Experimental Result –Near zero Speed



(a) Speed



(b) Rotor Fluxes

Fig 16. Experimental Result under Dynamic condition

Fig 14 a, 15a and 16a shows the experimental result of speed waveform under different test conditions. Fig 14b, 15b and 16b shows experimental rotor fluxes under various test conditions. The experimental results show the superiority of proposed fuzzy logic controller.

TABLE. III
INDUCTION MACHINE RATING AND PARAMETERS

Symbol	Meaning	Values
-	Rated shaft power	4 kW
-	Line to line voltage	400V
-	Rated speed	1430 RPM
P	Pole pair	2
f	Frequency	50 Hz
L_{ls}	Stator Leakage inductance	0.005839 H
L_{lr}	Rotor Leakage inductance	0.005839 H
L_m	Mutual inductance	0.1772 H
R_s	Stator resistance	1.405 ohm
R_r	Rotor resistance	1.395 ohm
J	Machine inertia	0.0131 kg m^2

6. Conclusion

A new Fuzzy logic based Model Reference Adaptive System is proposed. This system is stable in all four quadrants of operation of the speed sensorless vector controlled induction motor drive. Speed ripples are minimized with the proposed controller. However torque ripples are to be minimized to great extend. Torque peak overshoot in proposed Fuzzy controller is lower than conventional controller. The drive works well at low and zero speeds. These advantages are confirmed by the experimental results.

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