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A Novel Rotor Resistance Estimation Technique for Vector Controlled Induction Motor Drive Using TS Fuzzy

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ABSTRACT

Induction motor with indirect field oriented control is well suited for high performance applications due to its excellent dynamic behavior. However it is sensitive to variations in rotor time constant, especially variation in rotor resistance. In this study a scheme based on the Rotor flux Model Reference Adaptive Controller is used for on line identification of the rotor resistance and thus improving the steady state performance of the drive. The overriding feature of this estimation technique is the accurate identification of rotor resistance during transient and steady state conditions for drive operation at full load and at zero speed condition. Moroever, the effectiveness of the TS fuzzy controller utilizing rotor flux for online estimation of rotor resistance for four quadrant operation of motor drive is investigated and compared with the conventional PI and Mamdani fuzzy controller.Simulation results in MATLAB/Simulink environment have been presented to confirm the effectiviness of the proposed technique.

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1. INTRODUCTION

Till the beginning of 1980’s all such applications which require high speed holding accuracy, wide range of speed control and fast transient response used DC motor drives. Traditionally AC machines were used in applications like fan, pump and compressor which requires rough speed regulation and where the transient response is not critical [1]. The advances in the field of power electronics has contributed to the development of control techniques where the performance of an AC machine became comparable with that of a DC machine [2]. These techniques are known as vector control techniques and are classified as Direct/feedback field oriented control method (DFOC) and indirect/ feed forward method (IRFOC) [3]. The method depends on the determination of instantaneous rotor flux phasor position θ_e known as field angle or unit vector.

One of the main issues of vector control is its dependence on motor model and is therefore sensitive to the motor parameter variations [4]. The variations are mainly due to the saturation of the magnetizing inductance and the stator / rotor resistance due to temperature and skin effect. These variations will lead to error on the flux amplitude and its orientation along the d-axis. The system thus becomes unstable and also increases the losses in the system. In general the field oriented control method most commonly used in industries is the indirect field oriented control where the orientation of the flux space vector is estimated using the slip signal and the measured speed. However the feed forward adjustment of the slip signal requires knowledge of rotor resistance, rotor inductance and magnetizing inductance values and is estimated from the equivalent circuit model [5].

It has been given that the variations of rotor resistance and therefore the rotor time constant is the most critical in indirect field oriented vector controlled drives [6]. If this change is not estimated, the orthogonality between the synchronous frame $d_e - q_e$ variables is lost leading to cross coupling and poor dynamic performance of the drive system. Therefore major efforts were put in for online estimation of rotor resistance. The online parameter estimation technique can be broadly classified as spectral analysis technique, observer based technique, model reference adaptive system technique and artificial intelligence techniques [7-12].

The model reference adaptive systems scheme as shown in Figure 1 is the most popularly used for rotor resistance estimation because of its simpler implementation and less computational efforts compared to other methods. The technique proposes calculation of a parameter to be identified in two different ways [13-15]. The first calculation is based on references inside the control system known as the estimated value and the second known as the reference value depends on measured signals. One of the two values should be independent of the parameter which is to be estimated. The accuracy of this technique is based heavily on the machine model. The difference obtained between the reference and the estimated value is taken as an error signal and is used to drive an adaptive mechanism .Based on the formulation of the error signal the MRAC are further subcategorized as electromagnetic torque based, rotor flux based, $d_e - q_e$ voltage based and reactive power based. The adaptive mechanism normally uses a PI controller for the generation of the change in rotor resistance ΔR [16]. The PI controller may not give satisfactory performance for operating condition where frequent variation in motor speed and load torque is required. Fuzzy logic controllers as compared to PI controller do not require precise mathematical model,can handle nonlinearity and are more robust [17, 18]. Based on the rule consequent the fuzzy controllers are further classified as Mamdani and TS fuzzy controller. In TS-Fuzzy the linguistic rule consequent is made variable by means of its parameters and hence, it can produce an infinite number of gain variation characteristics [19] .Morever it has a definite edge over the Mamdani fuzzy due to the less number of fuzzy sets used for the inputs, leading to lesser rule sets.

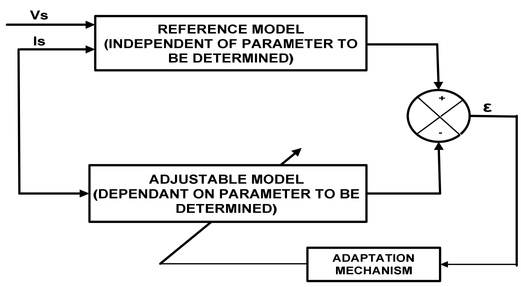


Figure 1. Block diagram of MRAC

As per the author's knowledge, no work has been reported where the TS fuzzy controller has been used as an adaptive mechanism for identification of rotor resistance based on Rotor Flux Model Reference Adaptive Controlller (RF-MRAC) instead of the existing PI and Mamdani fuzzy controllers as stated in paper [16-18]. In this paper the RF-MRAC using TS fuzzy controller as adaptive mechanism is devoloped and is investigated for an IRFOC induction motor drive.The objective of the proposed work is 1) to obtain an accurate online rotor resistance identification scheme for a four quadrant drive operation and also to minimize the over excitation/under excitation of the motor flux due to rotor resistance variations, 2) accurate identification of rotor resistance under symmetrical short circuit condition of rotor circuit and 3) to oberve the effectiveness of the identification technique when the drive is operating at zero speed with rated load torque condition. This paper evaluates the performance index of the rotor resistance identification as integral time square error (ITSE) for the proposed scheme and is compared with the other two controllers i.e. the PI and the Mamdani fuzzy.

The paper is organized as follows: Section 2 provides a brief overview of the dynamic modeling of the field oriented vector control drive. Section 3 describes the functions of the various block involved in the modeling of the vector controlled I.M drive and also the rotor resistance identification scheme using RF - .MRAC. Section 4 describes the Mamdani fuzzy control scheme as an adaptive mechanism of the rotor flux model reference adaptive system. Section 5 describes in detail the design and implementation of the proposed TS fuzzy control scheme as the adaptive mechanism of RF-MRAS. Section 6 details the simulation results of the PI, Mamdani and proposed TS fuzzy adaptive scheme under different drive operating conditions and conclusion is given in Section 7.

2. DESIGN FOR VECTOR CONTROL DRIVES

The dynamic model of induction motor for rotor flux oriented vector control application can be written as follows

$$p\begin{bmatrix} id_{se} \\ iq_{se} \\ \lambda d_{re} \\ \lambda q_{re} \end{bmatrix} = \begin{bmatrix} \frac{\_Rs}{\sigma Ls} & \omega e & \frac{\_Lm}{Lr\sigma Ls}p & \frac{\omega eLm}{Lr\sigma Ls} \\ -\omega e & \frac{-Rs}{\sigma Ls} & \frac{-\omega eLm}{Lr\sigma Ls} & \frac{-Lm}{Lr\sigma Ls}p \\ \frac{Lm}{Tr} & 0 & \frac{-1}{Tr} & \omega sl \\ 0 & \frac{Lm}{Tr} & -\omega sl & \frac{-1}{Tr} \end{bmatrix} \begin{bmatrix} id_{se} \\ iq_{se} \\ \lambda d_{re} \\ \lambda q_{re} \end{bmatrix} + \begin{bmatrix} \frac{vd_{se}}{\sigma Ls} \\ \frac{vq_{se}}{\sigma Ls} \\ 0 \\ 0 \end{bmatrix} \tag{1}$$

Where p denotes the derivative operator $\frac{d}{dt}$, id_{se}, iq_{se} are the stator currents and $\lambda d_{re}, \lambda q_{re}$ the rotor fluxes in $d_e - q_e$ frame. Similarly Rs, Ls, Rr and Lr are the stator résistance, stator self inductance, rotor resistance and the rotor self inductance respectively. The rotor time constant is given as$Tr = \frac{Lr}{Rr}$ and leakage inductance is σLs where $\sigma = 1 - \frac{Lm^2}{LsLr}$.

For rotor flux oriented control the rotor flux λr is directed along the *d*-axis and is equal toλd_{re} and therefore$\lambda q_{re} = 0$. Thus the equation (1a) modifies to as shown below

$$p\begin{bmatrix} id_{se} \\ iq_{se} \\ \lambda d_{re} \\ 0 \end{bmatrix} = \begin{bmatrix} \frac{\_Rs}{\sigma Ls} & \omega e & \frac{\_Lm}{Lr\sigma Ls}p & 0 \\ -\omega e & \frac{-Rs}{\sigma Ls} & \frac{-\omega eLm}{Lr\sigma Ls} & 0 \\ \frac{Lm}{Tr} & 0 & \frac{-1}{Tr} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} id_{se} \\ iq_{se} \\ \lambda d_{re} \\ 0 \end{bmatrix} + \begin{bmatrix} \frac{vd_{se}}{\sigma Ls} \\ \frac{vq_{se}}{\sigma Ls} \\ 0 \\ 0 \end{bmatrix} \tag{2}$$

From equation (2b) it can be seen that the $d_e - q_e$ axis voltage are coupled by the following terms:

$$v_d decoupling = \omega eiq_{se} - \frac{Lm}{Lr\sigma Ls}p\lambda d_{re} \tag{3}$$

$$v_q decoupling = \omega eid_{se} + \frac{\omega eLm}{Lr\sigma Ls} \tag{4}$$

To achieve linear control of stator voltage it is necessary to remove the decoupling terms and is cancelled by using a decoupled method that utilizes nonlinear feedback of the coupling voltage.

3. MODELING OF VOLTAGE CONTROLLED IM DRIVE WITH ROTOR RESISTANCE ESTIMATOR

The main aim of the vector control of induction motor is to control it just like a separately excited DC motor drive where one can obtain independent control of the two variables armature and field current which are orthogonal to each other thus having independent control over torque and flux. The block diagram of an indirect rotor flux oriented speed control of induction motor is shown in Figure 2. The scheme consists of the current control loop within the speed control loop. The scheme uses PI controllers for the d-axis and q-axis current whose proportional and integral gains are as shown in Appendix-III, the bandwidth of the inner current loop is chosen higher than the flux and speed controller. The voltage decoupling equations (3) & (4) are adjusted with the output of the controllers to obtain good current control action. The d-axis and q-axis reference voltages vd_{ref} and vq_{ref} thus obtained are transformed to the stationary i.e. stator reference frame with the help of field angle θ_e.The two phase voltage vd_{ss} and vq_{ss} in the stator reference frame are then transformed to three phase stator reference voltages v_a, v_b, v_c which acts as modulating voltage for the modulator by using the sine-triangle pulse width modulation (SPWM) scheme . The modulator output which is in the form of pulses is used to drive the IGBT with anti-parallel diode acting as switches for the conventional two level voltage source inverter (VSI).

As shown in Figure 2 the stator currents are measured and transformed as *d-q* axis currents, which are then used as feedback signals for the current controller. The *d-* axis current id_{se} is passed through a low pass filter with time constant equal to rotor time constant T_r to obtain the rotor flux which acts as feedback to the flux controller. The rotor speed ω_r, torque current iq_{se} rotor flux λd_{re} and rotor time constant T_r are used to determine the slip speed ω_{sl} and from it the rotor flux position θ_e for $e^{-j\theta_e}$ and $e^{j\theta_e}$ transformation.

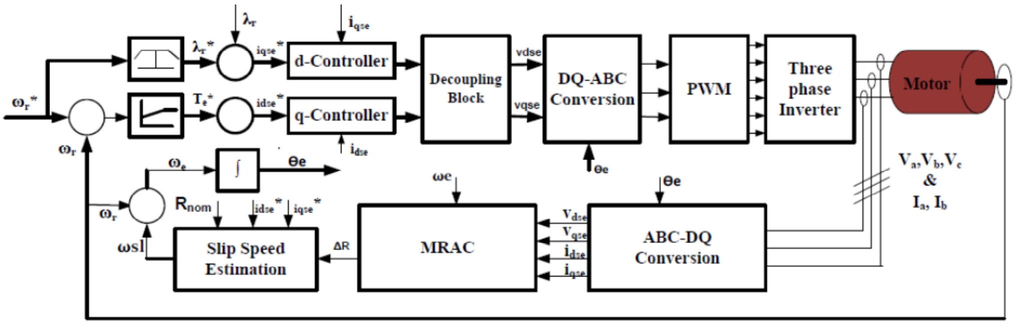


Figure 2. Block diagram of a voltage controlled IFOC drive.

a. Rotor Resistance Identification using Rotor Flux

The block diagram of the rotor flux based MRAC for identification of rotor resistance is shown in Figure 3, where the inputs v_a , v_b , i_a , i_b & ω_r are the motor terminal voltages, current and speed feedbacks. The rotor flux Ψr^v obtained from the voltage model which acts as the reference output of the model adaptive reference scheme is obtained by measuring the machine terminal voltage and currents, which are then transformed to the stationary reference frame as vd_{ss}, vq_{ss}, id_{ss} & iq_{ss}.

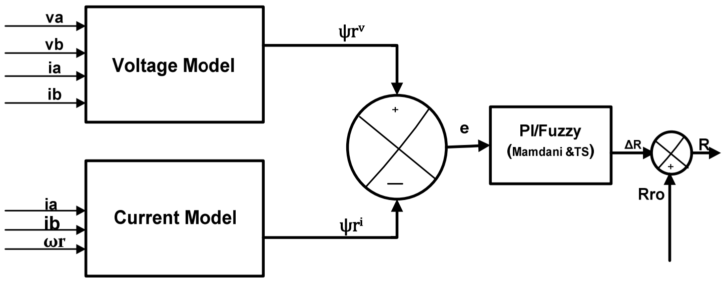


Figure 3. Proposed rotor flux based MRAC for rotor resistance estimation

The rotor flux $\Psi r^v = \sqrt{\Psi dr^{sv2} + \Psi qr^{sv2}}$ where Ψdr^{sv} and Ψqr^{sv} are the d-axis and q-axis rotor flux in the stationary reference frame which are derived as:

$$\Psi dr^{sv} = \frac{L_r}{L_m}(\Psi ds^{sv} - \sigma L_s id_{ss}) \quad (5)$$

and

$$\Psi qr^{sv} = \frac{L_r}{L_m}(\Psi qs^{sv} - \sigma L_s iq_{ss}) \quad (6)$$

given that Ψds^{sv}=$\int(vd_{ss} - R_s id_{ss})dt$ and Ψqs^{sv}=$\int(vq_{ss} - R_s iq_{ss})dt$ are the stator d-q flux in stationary reference frame, σ is the leakage inductance and R_s is the stator resistance.

Similarly the flux output $\Psi r^i = \sqrt{\Psi dr^{si^2} + \Psi qr^{si^2}}$ is obtained from the current model for the adjustable model is obtained by measuring the current and motor speed ω_r, where

$$\Psi dr^{si} = \int (\frac{L_m}{T_r} id_{ss} - \omega_r \Psi qr^s - \frac{1}{T_r}\Psi dr^s)dt \quad (7)$$

and

$$\Psi qr^{si} = \int (\frac{L_m}{T_r} iq_{ss} + \omega_r \Psi dr^s - \frac{1}{T_r}\Psi qr^s)dt \quad (8)$$

The difference between ψ_{r^v} and ψ_{r^i} acts as the error signal for the adaptive mechanism whose output indicates the change in rotor resistance ΔR which is then added up with the nominal resistance value i.e. R_{ro} to achieve the actual rotor resistance R_r.The obtained new value of R_r corresponding to change in rotor resistance is then used to determine the slip speed ω_{sl} and is added up with the rotor speed ω_r to obtain the synchronous speed ω_e.

4. IMPLEMENTATION OF FUZZY CONTROLLER

In this study the conventional PI controller as an adaptive mechanism has been replaced by Mamdani fuzzy controller. The fuzzy controller as shown in Figure 4 consists of two inputs $e_1(k)$ and $e_2(k)$and one output Δu. The input $e_1(k)$is the difference between the reference rotor flux "ψr^v" and actual rotor flux "ψr^i i.e. $e_1(k) = \psi r^v - \psi r^i$, and the input $e_2(k)$ which indicates the change in error and is given as $e_2(k) = e_1(k) - e_1(k-1)$. There are two normalizing factors k1&k2 for inputs e1and e2 and one de-normalizing factor for output Δu. In normalization process the input values are scaled in the range [-1, 1] and the de-normalization process converts the crisp output value of the fuzzy controller to a value depending on the output control element. In the fuzzifier the crisp values of input $e_1$and$e_2$are converted into fuzzy values [20]. For this purpose seven triangular fuzzy membership functions are defined for each input as well as the output.

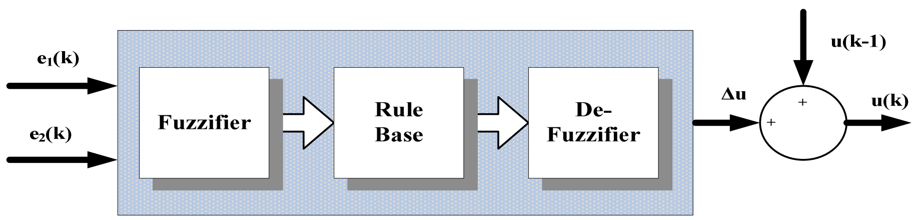


Figure 4. Block diagram of a Fuzzy controller

Figure 5 illustrates the triangle membership functions of the first input i.e. $e_1(k)$ which are defined by seven linguistic variables as Negative Big (NB) Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM) and Positive Big (PB). The overlap rates of the membership are taken as 50%.

The fuzzy rule base represent the knowledge of human operators who make necessary changes in the controller output to obtain system with minimum error and faster response. For this the behavior of the error signals$e_1(k)$ and $e_2(k)$ has to be observed and accordingly it is to be decided whether the controller output Δu is to be increased or decreased. The controller for the study make use of the sliding mode rule base shown in Figure 6 as it is easy to implement for real time application

The developed fuzzy logic uses the min – max compositional rule of inference. The inference mechanism of the fuzzy controller is implemented with regard to the rule base given by $\mu(\Delta u) = \min(\mu(e1), \mu(e2))$.

The defuzzifier process makes use of the centre of gravity method and is given as $\Delta\mu = \frac{\sum_{i=1}^{n} y_i \mu_{eo}(y_i)}{\sum_{i=1}^{n} \mu_{eo}(y_i)}$ where, n is the number of fuzzy sets in the output.

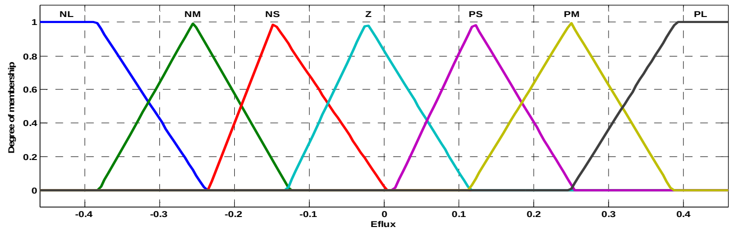


Figure 5. Input variable e1 (k) membership function

		$e2(k)$						
		NB	**NM**	**NS**	**Z**	**PB**	**PM**	**PB**
$e1(k)$	**NB**	**NB**	**NB**	**NB**	**NB**	**NM**	**NS**	**Z**
	NM	**NB**	**NB**	**NB**	**NM**	**NZ**	**Z**	**PS**
	NB	**NB**	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**
	Z	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
	PS	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**	**PB**
	PM	**NS**	**Z**	**PS**	**PM**	**PB**	**PB**	**PB**
	PB	**Z**	**PB**	**PM**	**PB**	**PB**	**PB**	**PB**

Figure 6. Mamdani Fuzzy rule base for rotor resistance estimation

5. DESIGN OF PROPOSED TS FUZZY CONTROLLER

The major difference betweenthe Mamdani and the TS fuzzy controller is that the former employ fuzzy sets as the consequent where as the later employ linear function as the consequent [21]. The linguistic rule consequent is made variable by means of its parameters and therefore the TS fuzzy control scheme can produce a large number of gain variations. For the study the input variables are $e_1(k)$ and $e_2(k)$ same as defined above.for Mamdani fuzzy. Each variable was fuzzified by two inputs fuzzy sets named as positive (P) and negative (N) respectively as shown in Figure 7. The mathematical representation of positive and negative membership function for the input variables are given below.

$$\mu P(xi) = \begin{cases} 0, x(i) < -L \\ \frac{x(i)+L}{2L} \quad , -L \le x(i) \le L \\ 1, x(i) > L \end{cases} \tag{9}$$

$$\mu N(\,xi) = \begin{cases} 1, x(i) \le -L \\ -\frac{x(i)+L}{2L} \;, -L \le x(i) \le L \\ 0, x(i) > L \end{cases} \tag{10}$$

The value of $\mu P(xi) and\ \mu N(xi)$ is either 0 or 1 when $x(i)$ is outside the interval [-L, L]. The value of L plays an important role in the controller performance and should be judiciously chosen. As there are two fuzzy sets for each input, there will be (2 x 2) fuzzy values to cover all these combinations. The fuzzy control rules for the two inputs use the following simplified rules as shown in Table 1.

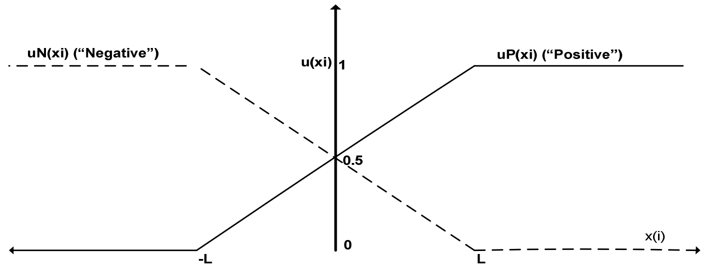


Figure7. Input variables membership function

Table 1. TS fuzzy rule set

Rule No.	IF $e1(k) is$	AND $e2(k)$	THEN
R1	Positive	Positive	$v1k = k1(a1 * e1(k) + a2 * e2(k))$
R2	Positive	Negative	$v2(k) = k2 * v1(k)$
R3	Negative	Positive	$v3(k) = k3 * v1(k)$
R4	Negative	Negative	$v4(k) = k4 * v1(k)$

The corresponding incremental output Δu of the fuzzy controller is

$$\Delta u(k) = \sum_{i=1}^{4} \mu i v i(k) = v1(k) * \frac{\sum_{i=1}^{4} \mu i k i}{\sum_{i=1}^{4} \mu i} \quad (11)$$

where $v1(k) = (a1 * e1(k) + a2 * e2(k))$

For this study the algorithm of the proposed TS fuzzy controller is developed and programmed in MATLAB M-file and is then used as a Simulink block in the model with the help of Embedded M Function block available in the MATLAB/Simulink library. The values of the six constants $k1, k2, k3, k4\ \ a1\ and\ \ a2$ as given in Appendix-II are determined by trial and error with performance indice as the integral time square error of e_1(k). In general the number of unknown constants for 2^M rules are given by$\lambda = M + 2M$, where M stands for the number of inputs.

6. RESULTS AND ANALYSIS

A simulation model of voltage controlled IRFOC as shown in Figure 2 is developed in a MATLAB/Simulink environment to ascertain the effectiveness of the proposed adaptive algorithm. The parameters and ratings of the test motor are given in Appendix-I. The SPWM based indirect rotor flux oriented controller is tested for step increase in rotor resistance by connecting a three phase star connected resistor bank to the rotor of the three phase slip ring induction motor externally. Similarly a step decrease in rotor resistance is obtained by instrumenting the wrong rotor resistance value in the controller. The simulation time used are only to explain the concepts, as such sudden practical changes in rotor resistance due to temperature variation rarely occurs in practice due to the large thermal time constant of the motor. The IRFOC drive is subjected to different operating conditions noted as Case-II to IV below, during which step increase and decrease in rotor resistance is initiated to test the effectiveness of the adaptive mechanism. Under these operating conditions the performance analysis of the proposed TS fuzzy controller based RF-MRAC in terms of settling time and steady state error is made and is compared with the other established controllers i.e. the PI and Mamdani fuzzy controller.

6.1. Case-I: Speed and Load Torque Constant with RF-MRAS Disabled

The IRFOC drive is operated at constant speed set of 1000 rpm and load torque of 4 Nm. as shown in Figures 8 and 9. A step change in motor rotor resistance above by 50% and below by 30% of its nominal value R_{nom} is done at t=12sec with rotor flux model reference adaptive mechanism kept inactive. From Figure 10 (a) & (b) it is observed that the actual and the reference value of the d-axis flux remains same i.e. 0.936 ωb till the instrumented and actual value of rotor resistance are equal. At t=12 sec when the change in rotor resistance is initiated it is seen that, the increase in rotor resistance has resulted in sudden changes in the motor actual flux with its value increasing from 0.936 ωb to 1.195ωb. Similarly the decrease in rotor resistance has resulted in the actual flux decreasing from 0.936 ωb to 0.6 ωb respectively. The increase in rotor flux may lead to over excitation of the motor resulting in increased core losses and saturation. It also seen from Figure11 that the electromagnetic developed by the motor has also decreased when the rotor resistance is decreased.

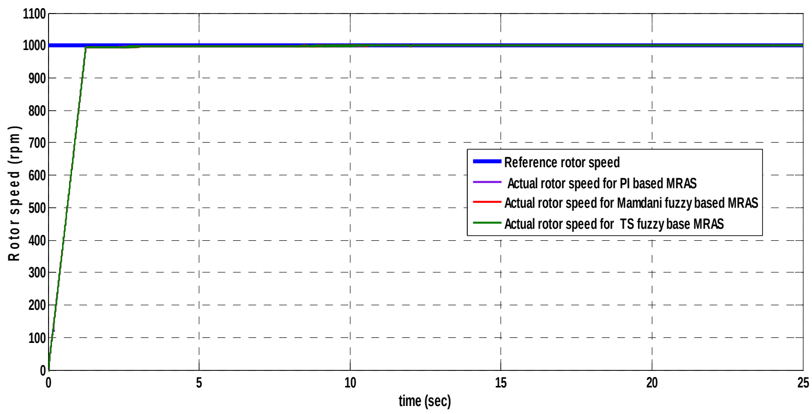


Figure 8. Tracking of constant speed reference of 1000 rpm

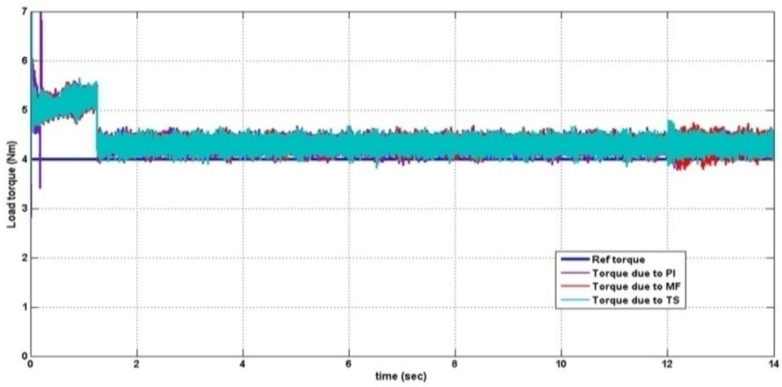
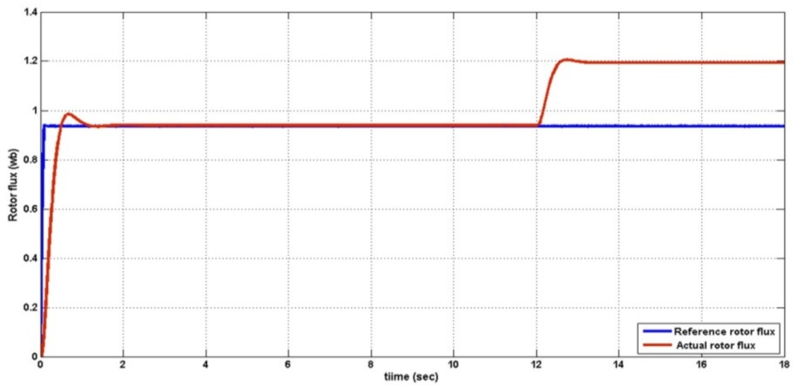
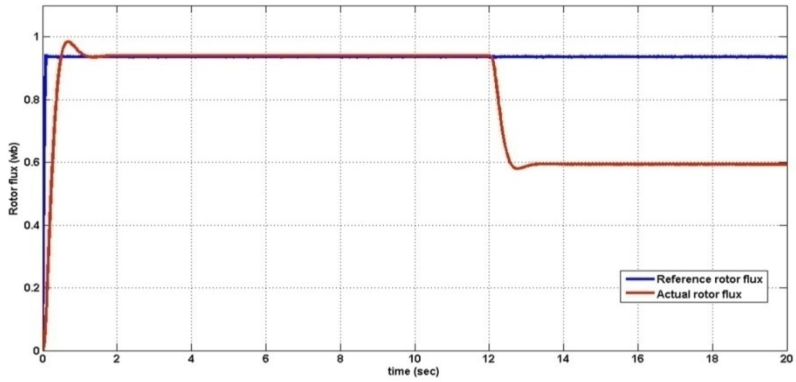


Figure 9. Tracking the constant load torque reference 4Nm



(a)



(b)

Figure 10. Rotor flux for step (a) increase (b) decrease in rotor resistance with identification disabled

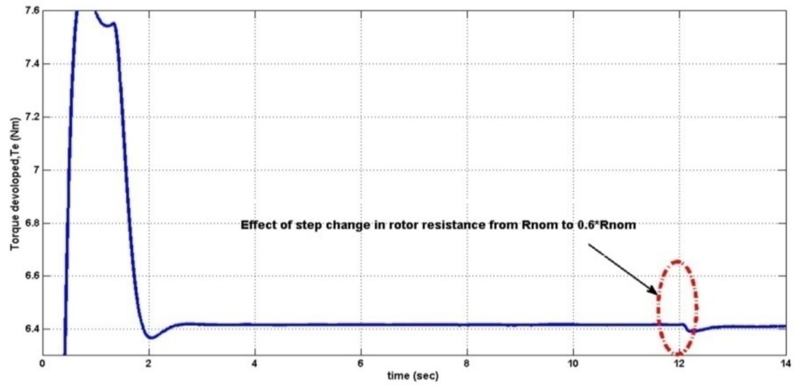
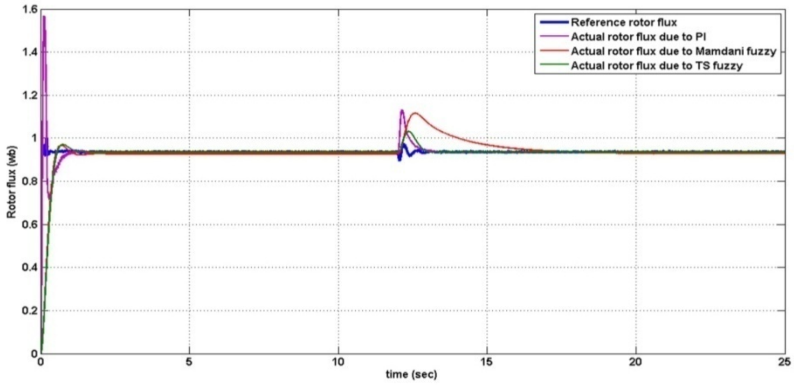


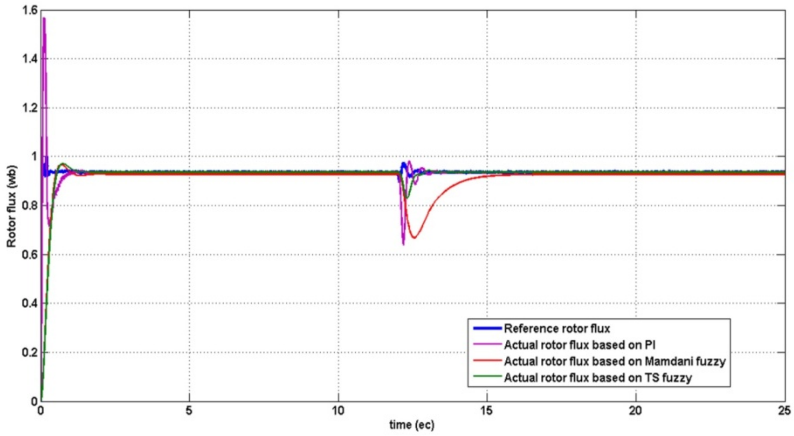
Figure 11. Effect on Torque devolped for step increase in rotor resistance with identification disabled

6.2. Case-II: Speed and Load Torque Constant with RF-MRAS Enabled

The IFOC drive is now subjected to the same operating condition as above, with step change in rotor resistance at t = 12 sec. The integral time square error performance index is used for finding the coefficients k_p and k_i of the PI controller acting as the adaptive mechanism and are found to be 5 and 80 respectively. It is observed from Figure 12 (a) and (b) that during motor starting condition with PI controller, peak overshoot of rotor flux occurs which lasts for about 1.5sec before tracking the reference flux value whereas for Mamdani and TS fuzzy controller no such overshoot in rotor flux during starting transient is observed. At t=12 sec the change in resistance has resulted in increase of the d-axis flux from its nominal value of 0.936 ωb for all the three controllers with peak overshoot again more pronounced for the PI controller before settling to its steady state flux value. From Figure 13 (a) & (b) it is also seen that the performance of the TS fuzzy controller is excellent as it can track the step change in rotor resistance in 1.5 sec compared to the other two controllers with its steady state error taken as integral time square error (ITSE) very low as shown in Table 2. The same performance index is obtained from the TS fuzzy controller when the instrumented value of the rotor resistance is made less than the actual motor resistance value.

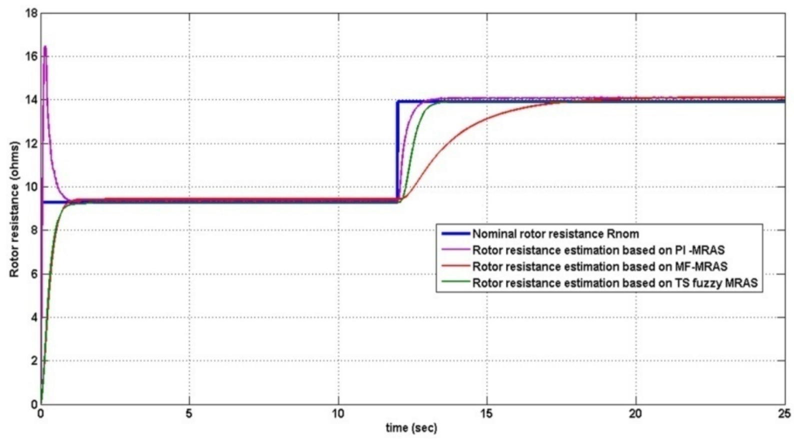


(a)

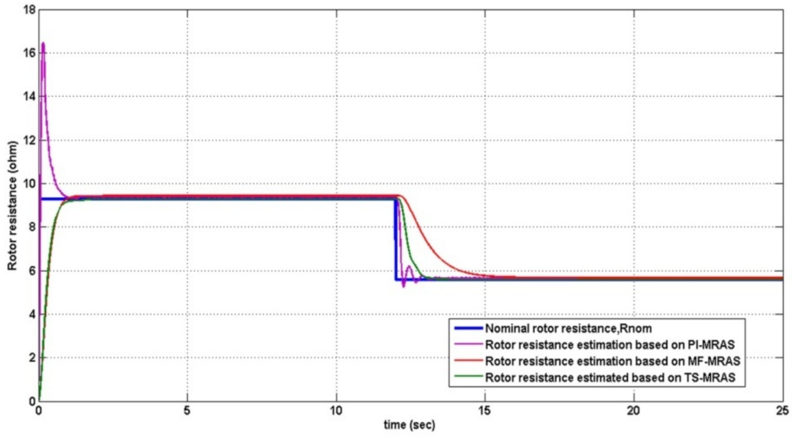


(b)

Figure12. Rotor flux for step (a) increase (b) decrease in rotor resistance, Case-II



(a)



(b)

Figure13. Rotor resistance identification for step (a) increase (b) decrease in rotor resistance, Case-II

6.3. Case III: Variable Motor Speed with Constant Load with RF-MRAS Enabled

The IFOC drive is subjected to speed changes as shown in Figure 14 where the drive operates at 1000 rpm from 2-16 sec and then operates at zero speed at full load torque from 16-22 sec and thereafter operates in the reverse direction at 500 rpm from 22 -25 sec. exhibiting the condition of industrial overhead crane drive. The step increase and decrease in rotor resistance as described above is again initiated at t =12sec. It is seen from Figure 15 (a) that the actual flux oscillates from its reference value with PI adaptive mechanism during motor starting and again sustained oscillation in rotor flux is observed when it is rotating in the reverse direction, which becomes more pronounced when the step decrease in rotor resistance is made as seen in Figure 15 (b) It is also observed from Figure 16 (a) the steady state error in terms of rotor resistance estimation is the lowest for TS fuzzy., but its performance when the rotor resistance is decreased detoriates considerably when compared with Mamdani fuzzy controller and also sustained oscillations in rotor resistance estimation is obseverd in Figure 16 (b) when the drive is operating at zero speed.

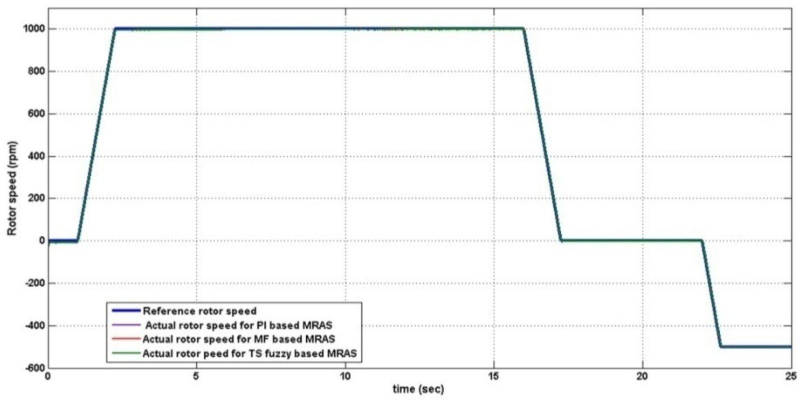
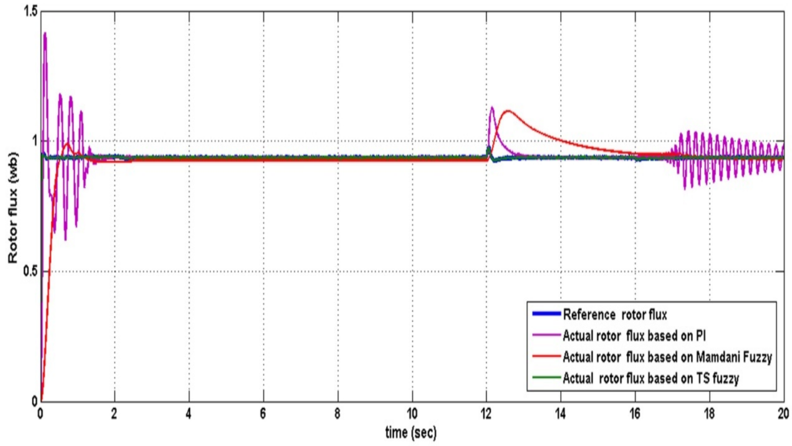
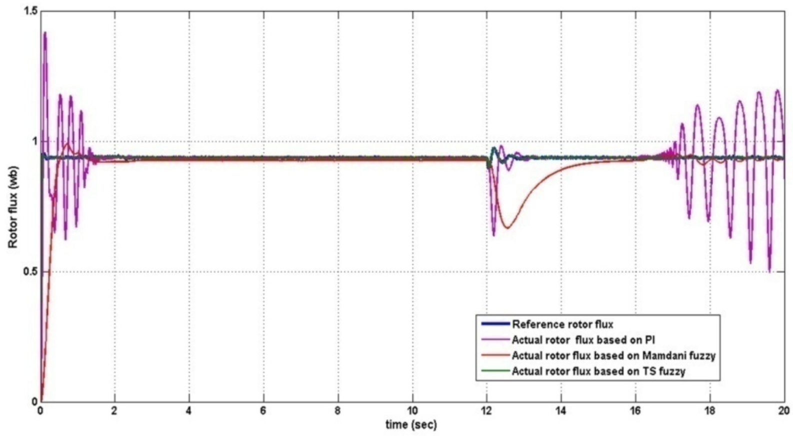


Figure 14. Variable reference rotor speed track for step increase in rotor resistance

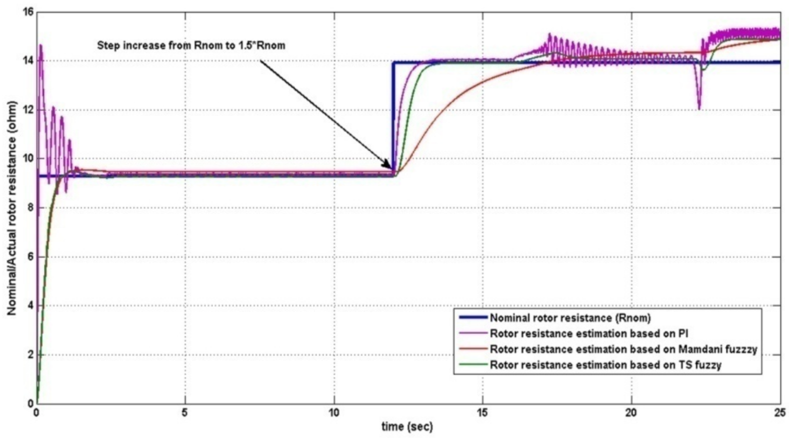


(a)

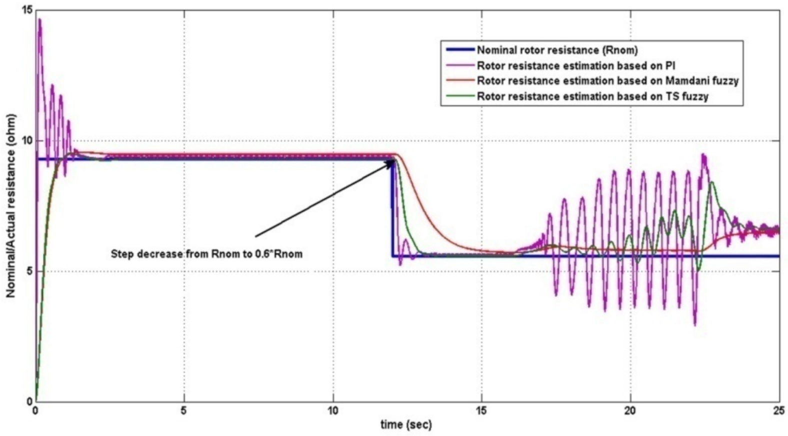


(b)

Figure 15. Rotor flux for step (a) increase (b) decrease in rotor resistance, Case-III



(a)



(b)

Figure 16. Rotor resistance identification for step (a) increase (b) decrease in rotor resistance, Case-III

6.4. Case IV: Motor Speed Constant with Variable Load Torque and RF-MRAS Enabled

The IRFOC drive is subjected to variable load torque as shown in Figure 17 depicting the operating condition of a crusher motor drive with load torque T_L made negative equal to 2 Nm at t=22sec representing regenerative braking condition. It is very well observed from Figure 18 (a)& (b) and from Figure 19 (a) & (b) that amongst the three controllers the steady state error in terms of rotor flux and estimation of rotor resistance value is the lowest for TS fuzzy controller as shown by the performance index listed in Table 2.

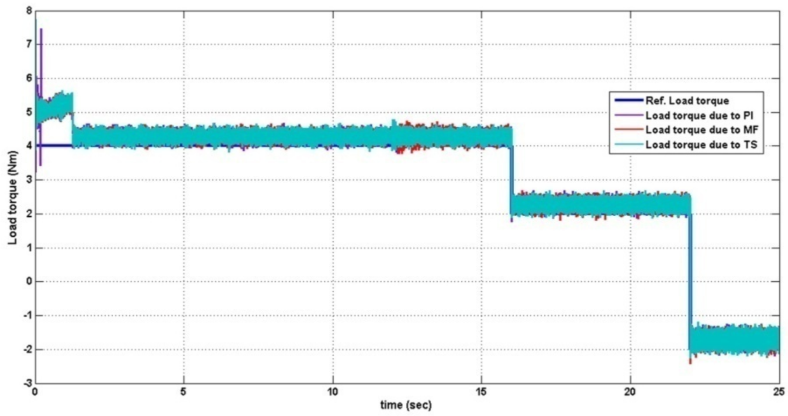
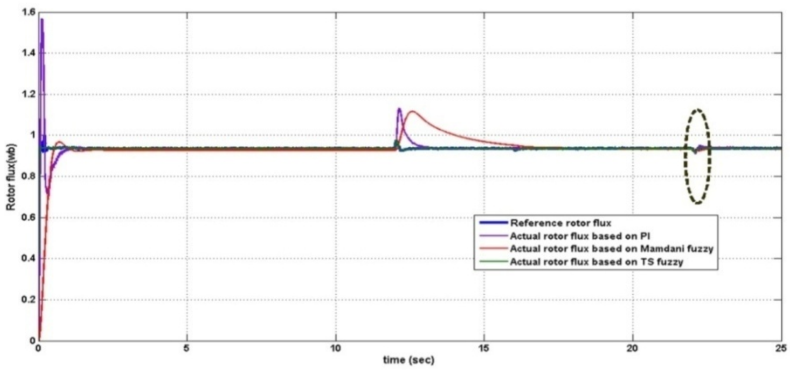
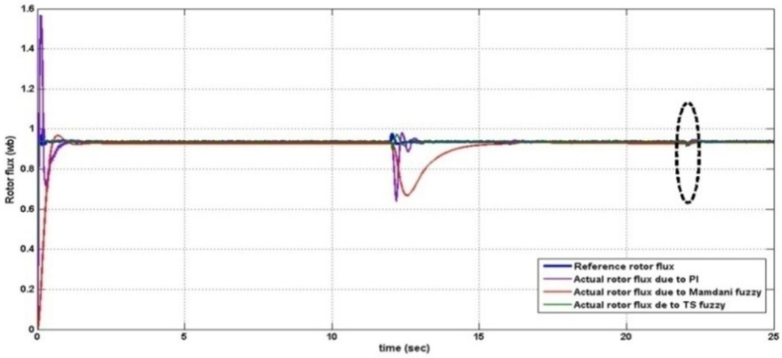


Figure 17. Tracking of variable torque reference with RF-MRAS enabled

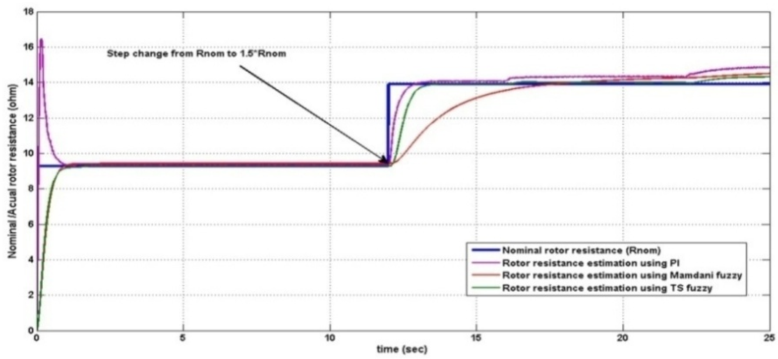


(a)

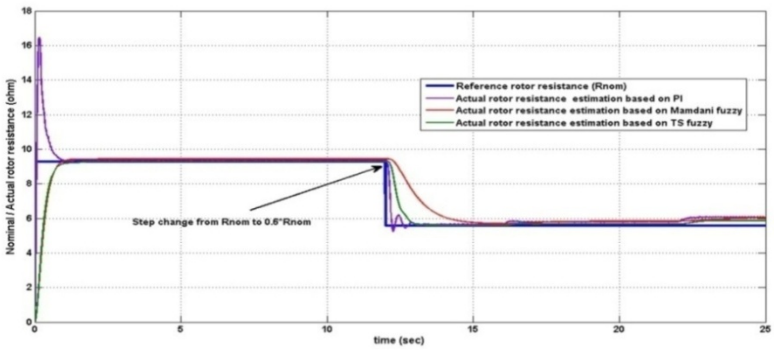


(b)

Figure 18. Rotor flux for step (a) increase (b) decrease in rotor resistance, Case-IV



(a)



(b)

Figure 19. Rotor resistance identification for step (a) increase (b) decrease in rotor resistance, Case-IV

7. CONCLUSION

A new approach for the rotor resistance identification of induction motor drive based on rotor flux model reference adaptive system using TS fuzzy controller as an adaptive mechanism has been presented. The identification is online and is based on the steady state model of indirect field oriented controller. From the investigations it can be appreciated that the performance of the TS fuzzy controller is better than the PI and Mamdani fuzzy controller under stringent motor operating condition as well as when the drive is under zero speed operating condition. It is observed from the simulation results that the d-axis flux settles approximately in 2-2.5 sec and its peak overshoot during change in operating condition or motor rotor resistance parameter variation is less compared to the other two controllers. Moreover, it is also observed from the results that leaving apart Case- III. (b) which, of course can be improved by optimizing the fewer no of TS fuzzy parameters as compared to Mamdani fuzzy using Evolutionary Algorithm, the tracking of change in rotor resistance by TS fuzzy controller in terms of steady state error (ITSE) and peak overshoot is superior to both PI and Mamdani fuzzy controller.

Table 2. Comparison of controller performance with regard to rotor resistance identification for step (a) increase (b) decrease in I.M rotor resistance at t=12 sec for Case II-IV

Description		**Controller Type**		
		PI	**Mamdani Fuzzy**	**TSFuzzy**
		Steady State error (ITSE)	Steady State error (ITSE)	Steady State error (ITSE)
CCase II	(a)	4.738	4.929	0.01505
	(b)	1.201	2.067	0.06346
CCase III	(a)	102.4	46.91	45.32
	(b)	150	45.61	184.6
CCase IV	(a)	62.52	20.87	7.43
	(b)	22.64	17.79	6.6

APPENDIX-I

Parameters of the IM used

Ratings

Power: - 0.746 KW. Frequency: - 50Hz, Voltage:-415V, Stator current:-1.8Amp, Speed:-1450 rpm, Pole pair:-2

Machine constants

Stator Resistance (R_s) = 10.75 Ω., Rotor Resistance (R_r) = 9.28 Ω, Stator/Rotor Self Inductance (L_s/L_r) =0.5318 H Moment of Inertia (J) = 0.011787 kgm^{2,} Friction coefficient (B) = 0.0027 Nm/rad/sec

APPENDIX-II

TS Fuzzy Parameters Used In Simulation: a1 = 3; a2 = 1.5; k1 = 1.18; k2= 0.15; k3=0; k4= 5;

APPENDIX-III

Proportional (k_p) and Integral (k_i) Gains of PI Controller

PI Controller	k_p	k_i
Speed control loop	1.295	0.2967
Flux control loop	110.6	1083.5
Inner $d_e - q_e$ current loops	98.61	9087.04

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