Performance Improvement of an Induction Motor Drive using Feedback Linearization and Fuzzy Torque Compensator

K. B. Mohanty, *Member, IEEE*, and Madhu Singh

Abstract— **This paper presents the dynamic modeling and simulation of a feedback linearization scheme for high performance induction motor control which decouples the rotor flux and the rotor speed (torque) control loop. In this scheme the controller takes rotor flux from the feedback path and uses it for the cancellation of nonlinearity present in the rotor flux and the rotor speed control signal. As direct flux measurement is proved not to be suitable due to the need of sensor and the sensor in itself sensitive to temperature .The scheme uses a flux estimator. Furthermore the process is implemented on the stationary reference frame. This offers less complex method than the Vector Control Scheme where the requirement for the precise knowledge of the instantaneous position of space flux and the transformation of a synchronous coordinates system into a structure of stationary reference frame and vice-versa makes the system more complex. Like vector control it uses PI controller for speed and flux. To confront the problem of uncertainties fuzzy controller is used. The control scheme is simulated in MATLAB environment. Simulation result demonstrates good performance and makes it fair competitive to the other high performance schemes of Induction motor.**

Index Terms-- **Feedback linearization, Flux estimator, Stationary reference frame, Proportional integral controller, Fuzzy torque compensator.**

I. Introduction

Recently the subject of nonlinear control is occupying an increasingly important place in automatic control engineering and has become a necessary part of the fundamental background to control engineering [1]-[2].Its potential application in the area of induction motor control is emerging as the thrust area for research work. The induction motors are the most preferred for industrial application because of its simplicity, reliability, low cost, ruggedness, and suitability to work in volatile environment. It does not require maintenance and is pollution free. So it is also acceptable in automation industries. But it requires complex control strategy, because it possesses three inherent drawbacks as follows. (a)It is a higher order nonlinear dynamic system with internal coupling,(b) Some state variables like rotor currents and fluxes, are not directly measurable, (c) Variation in parameters like rotor resistance due to temperature and magnetizing inductance due to saturation have significant impact on the system dynamics.

Many attempts have been made in past to optimize the performance and simplify the control strategy of the induction motor. Out of these Field Oriented Control or Vector Control proposed by Blaschke [3] and Hasse [4] has emerged successfully to achieve the high performance requirement. As a result it has been aggressively accepted by the automation industries by replacing bulky, costly DC motor drive which has commutation problem.

The vector control methods are complex to implement. Because in vector control method, the decoupling relationship is obtained by means of a proper selection of state coordinates, under the hypothesis that the rotor flux is kept constant. The torque is only asymptotically decoupled from the flux i.e., decoupling is obtained only in steady state, when the flux amplitude is constant. Coupling is still present, when flux is weaken in order to operate the motor at higher speed within the input voltage saturation limit or when flux is adjusted in order to maximize power efficiency [5].

This has further led to introduction nonlinear geometric control theory particularly feedback linearization, which can achieve completely decoupled torque and flux amplitude of the induction motor [9]-[18]. But for the satisfactory performance, the motor parameters of the controlled plant must be precisely known and accurate knowledge of the flux is required. In the last decade, a good number of research work has been reported incorporating various control schemes to simplify and to enhance the performance .The work includes several methods for accurate estimation of flux. But the control performance is still influenced by the uncertainties of the plant. Therefore, the motivation behind this work to design a suitable robust control scheme to combat the uncertainties arising in practical application.

In this work, a feedback linearization approach for induction motor is developed. The control scheme is implemented with two methods. In one method two PI

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controllers are used for controlling speed and secondary flux. Simulation results show the complete decoupling of the rotor flux and rotor speed loop. However, the control performance in practice still influenced by the parameter variation and plant uncertainties. and remarkable oscillation appears in the torque response. The uncertainties in the plant can well be taken care by fuzzy logic based controller [19]-[22]. Therefore, in another scheme a fuzzy logic based torque compensator is incorporated, which reduces ripples in the torque and also compensate it.

II. SYSTEM DESCRIPTION

The schematic block diagram of the proposed system is shown in Fig 1. The scheme consists of four controllers, one flux estimator, a current controlled PWM voltage source inverter and induction motor. The PI controller regulates flux and speed and third fuzzy PI controller regulates torque and compensates torque ripples. Voltage model [6] is used for flux estimation. Output of flux and fuzzy torque regulator and also estimated flux are the input to the decoupling controller and its output goes to the current regulator. Output of current regulator is utilized to generate gate drive signal for PWM VSI inverter, which forces reference current in the motor to develop required torque. The control scheme is implemented with two methods. In one method two PI controllers are used for controlling speed and secondary flux. In another scheme a fuzzy logic based torque compensator is in series with PI speed controller, which reduces ripples in the torque and also compensates it.

III. MODELING OF INDUCTION MOTOR

The dynamic equations representing induction motor in the α-β stator fixed frame are as

$$\dot{i}_{\alpha s} = -\frac{1}{\sigma L_s}\left(R_s + \frac{L_m^2}{L_r^2}R_r\right)i_{\alpha s} + \frac{1}{\sigma L_s}\frac{L_m R_r}{L_r^2}\psi_{\alpha r} + \frac{pL_m}{\sigma L_s L_r}\omega_r\psi_{\beta r} + \frac{V_{\alpha s}}{\sigma L_s} \tag{1}$$

$$\dot{i}_{\beta s} = -\frac{1}{\sigma L_s}\left(R_s + \frac{L_m^2}{L_r^2}R_r\right)i_{\beta s} + \frac{1}{\sigma L_s}\frac{L_m R_r}{L_r^2}\psi_{\beta r} - \frac{pL_m}{\sigma L_s L_r}\omega_r\psi_{\alpha r} + \frac{V_{\beta s}}{\sigma L_s} \tag{2}$$

$$\dot{\psi}_{\alpha r} = -\frac{R_r}{L_r}\psi_{\alpha r} - p\omega_r\psi_{\beta r} + \frac{L_m R_r}{L_r}i_{\alpha s} \tag{3}$$

$$\dot{\psi}_{\beta r} = -\frac{R_r}{L_r}\psi_{\beta r} + p\omega_r\psi_{\alpha r} + \frac{L_m R_r}{L_r}i_{\beta s} \tag{4}$$

$$\dot{\omega}_r = -\frac{B}{J}\omega_r + \frac{1}{J}(T_e - T_l) \tag{5}$$

where, $\sigma = (1 - \frac{L_m^2}{L_s L_r})$ is the leakage coefficient , ($i_{\alpha s}$,$i_{\beta s}$) ($\psi_{\alpha r}$, $\psi_{\beta r}$), ($V_{\alpha s}$,$V_{\beta s}$) are respectively the α-β component of the stator current, rotor flux and stator voltage, (R_s,L_s), (R_r,L_r) are stator and rotor parameters (resistance and inductance), and $L_m$is magnetizing inductance and ω_r is the motor speed.

The electromagnetic torque developed is given by

$$T_e = K_T(\psi_{\alpha r}i_{\beta s} - \psi_{\beta r}i_{\alpha s}),\ K_T = \frac{3pL_m}{2L_r} \tag{6}$$

where, p is the number of pole pairs.

IV. FEEDBACK LINEARIZATION

Feedback linearization is an approach to nonlinear control design which has attracted great deal of research interest in recent years. The central idea of the approach is to algebraically transform a nonlinear system dynamics into a fully or partially linear one so that linear control technique can be applied. This differs entirely from conventional linearization techniques. Feedback linearization is achieved by exact state transformation. Therefore, it uses a nonlinear transformation on system variables expressing them in a new suitable coordinate system which enables the introduction of a feedback, so that an input-output or state linearization in new coordinates is achieved. The theoretical foundation and a systematic approach can be found in [1].

In order to control the induction motor in field orientation schemes to get a dc motor like performance, the rotor speed and rotor flux must be decoupled. Therefore, output to be controlled is chosen as

$$Y^T = [\omega_r, \psi_r] \tag{7}$$

Where, ω_r is rotor speed and Ψ_r is the rotor flux. The rotor flux calculated as

$$\psi_r^2 = \psi_{\alpha r}^2 + \psi_{\beta r}^2 \tag{8}$$

The time derivative of ψ_r is

$$\dot{\psi}_r = \frac{1}{\psi_r}\left[\psi_{\alpha r}\dot{\psi}_{\alpha r} + \psi_{\beta r}\dot{\psi}_{\beta r}\right] \tag{9}$$

Substituting $\dot{\psi}_{\alpha r}$ and $\dot{\psi}_{\beta r}$ from equation (3) and (4) into equation (9)

$$\dot{\psi}_r = \frac{1}{\psi_r}\left[\psi_{\alpha r}\left(-\frac{R_r}{L_r}\psi_{\alpha r} - p\omega_r\psi_{\beta r} + \frac{L_m R_r}{L_r}i_{\alpha s}\right) + \psi_{\beta r}\left(-\frac{R_r}{L_r}\psi_{\beta r} + p\omega_r\psi_{\alpha r} + \frac{L_m R_r}{L_r}i_{\beta s}\right)\right] \tag{10}$$

Simplifying equation (10) and we have state equation of the rotor flux as

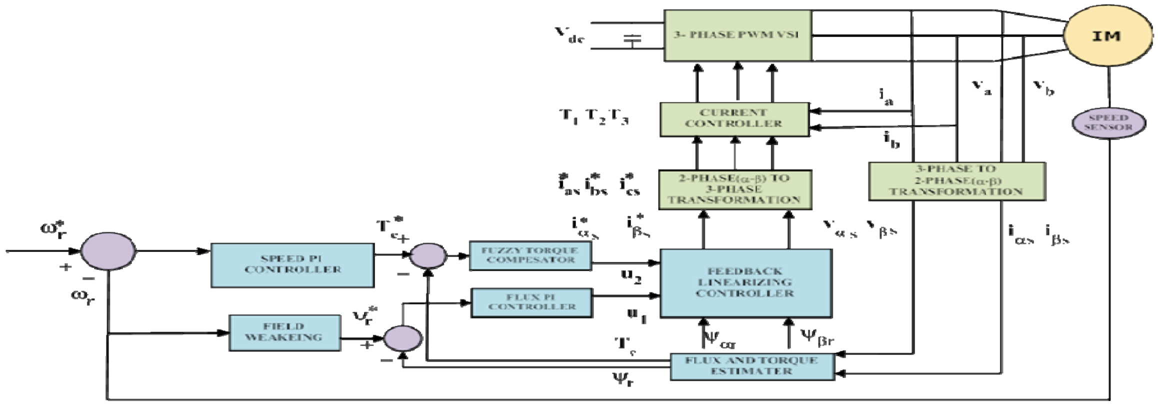

Fig 1 Schematic diagram a linearized induction motor with PI controller and fuzzy torque compensator

$$\dot{\psi}_r = -\frac{R_r}{L_r}\psi_r + \frac{L_m R_r}{L_r \psi_r}(i_{\alpha s}\psi_{\alpha r} + i_{\beta s}\psi_{\beta r}) \tag{11}$$

And from equation (5) And (6) state equation of rotor speed is

$$\dot{\omega}_r = -\frac{B}{J}\omega_r + \frac{1}{J}K_T(\psi_{\alpha r} i_{\beta s} - \psi_{\beta r} i_{\alpha s}) - \frac{1}{J}T_l \tag{12}$$

The state equations (11) and (12) describe flux and mechanical system, which has $i_{\alpha s,}$ and $i_{\beta s}$ two control inputs ψ_r and ω_r are the two outputs. Thus, it represents a coupled system. Since, there are no direct relations between the outputs and inputs. Therefore, the nonlinear feedback theory [1] is used to eliminate this coupling relationship between the control inputs $i_{\alpha s}$, $i_{\beta s}$ and the system outputs ψr and ω_r. Let $u1$ and $u2$ be taken as two new control input which converts coupled system into uncoupled one [15]. The equation (11) and (12) with new control input can be rewritten as

$$\dot{\psi}_r = -\frac{R_r}{L_r}\psi_r + \frac{L_m R_r}{L_r}u1 \tag{13}$$

$$\dot{\omega}_r = -\frac{B}{J}\omega_r + \frac{1}{J}K_T u2 - \frac{T_l}{J} \tag{14}$$

Thus, the new inputs $u1$ and $u2$ can be used to control the rotor flux and motor speed via following PI controllers [5].

$$u1 = K_{p1}(\psi_r^* - \psi_r) + K_{i1}\int_0^t (\psi_r^* - \psi)dt \tag{15}$$

$$u2 = K_{p2}(\omega_r^* - \omega) + K_{i2}\int_0^t (\omega_r^* - \omega)dt \tag{16}$$

From equation (11). (12), (13) and (14) the expression for control inputs can be written as [15]

$$u1 = \frac{1}{\psi_r}(\psi_{\alpha r} i_{\alpha s} + \psi_{\beta r} i_{\beta s}) \tag{17}$$

$$u2 = (\psi_{\alpha r} i_{\beta s} - \psi_{\beta r} i_{\alpha s}) \tag{18}$$

Rewriting the equations (17) and (18) for derivation of $i_{\alpha s}$ and $i_{\beta s}$ in terms of $u1$ and $u2$.

$$i_{\alpha s} = \frac{\psi_{\alpha r}}{\psi_r}u1 - \frac{\psi_{\beta r}}{\psi_r^2}u2 \tag{19}$$

$$i_{\beta s} = \frac{\psi_{\beta r}}{\psi_r}u1 + \frac{\psi_{\alpha r}}{\psi_r^2}u2 \tag{20}$$

The above equations (19) and (20) represent a feedback linearization decoupling controller. The block of feedback linearizing controller is shown in Fig.1.

V. Design Of Fuzzy Logic Torque Compensator

Fuzzy torque controller is design on the basis of reasoning theory of fuzzy set algorithm. The fuzzy controller is comprises of three functional blocks namely, the fuzzifier, the decision maker and the defuzzifier. The essential inputs are the rule based and data based blocks. The block structure is shown in Fig .2. The fuzzifier converts the crisp data into linguistic format. The decision maker decides in the linguistic format base and relevant data supplied by the data base. The defuzzifier block and the linguistic format signal is converted back into the numeric form (crisp form). The decision making block uses the rules in the format of “If-Then-Else”,.

For this Scheme a fuzzy torque compensator is designed and connected in cascade to the PI speed controller. Reference torque, which is the output of the speed controller and the actual estimated torque are input signals to the fuzzy torque compensator ,which eliminate undesired features appearing in the response with conventional PI controller, such, as torque ripple, overshoot, and steady state error. The processing is shown in Fig 2.

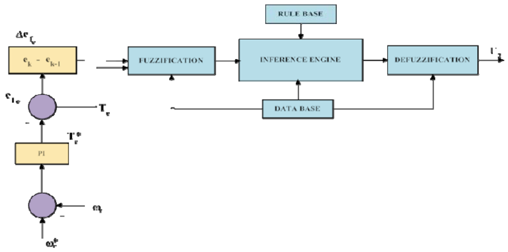

Fig 2. Schematic diagram of fuzzy torque compensator

According to the fuzzy logic (FL) principle the controller action proceeds as follows.

(i) Computation of the value of the two inputs

- Reference torque T^*_e and estimated torque T_e are sampled.
- Torque error(e(t)) and rate of change of torque error(Δe(t)) pu is computed and fed to the fuzzifier.

e(t) in per unit = $(T^*_{en} - T_{en}))/T^*_{en}$ (22)

Rate of change of error in per unit = $(e(t)_n\text{-}e(t)_{n-1})/T$ (23)

Where, T is the sampling interval.

ii) Fuzzification

- Scaling of input signal by suitable scaling factors.
- Limiting the input data between +1.0 and -1.0 boundaries.
  if input is greater than +1.0, then input equal to +1.0
  If input is less than -1.0, then input equal to -1.0
  If input is greater than -1.0 and less than +1.0, then it remains same
- Input data is converted into linguistic format in accordance with the defined fuzzy sets in accordance to Fig.3

(iii) Inference

The linguistic value of the output signal is determined according to the linguistic rule. The fuzzy rules are stated in Table I. As objective of the compensator is to compensate the chattering signal around reference torque, there only 16 rules are sufficient to achieve the objective.

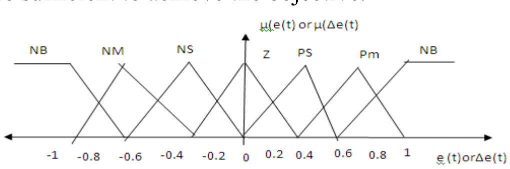

Fig.3 Illustration of membership function and inputs

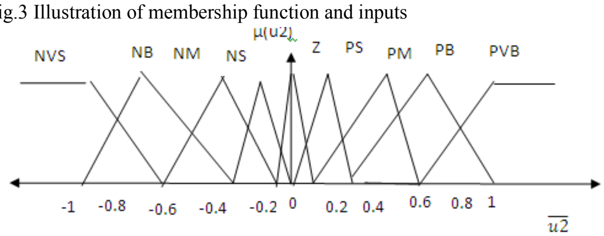

Fig.4 Illustration of membership functions and output variable

(iv) De-fuzzification

It is the process of determining the numerical value to represent a given fuzzy set. It involves following steps

- α= min[μ(e(t),μ(Δe(t)],where α, represents degree of fulfillment (DOF) and μ represents "membership of".
- Latest instant α should be maximum of represents instant values.
- Crisp value = C[∑p(m). α/ ∑ α], where p(m) is the location of the peak membership function and C is the scaling factor.

Table I
Linguistic rule for PI- Fuzzy logic controller

e(t)/Δe(t)	NB	NM	NS	Z	PS	PM	PB
NB				NB			Z
NM				NM			PS
NS				NS			PM
Z	NB	NM	NS	Z	PS	PM	PB
PS				PS			
PM				PM			
PB				PB			

VI. ROTOR FLUX ESTIMATION

The knowledge of rotor flux is essential for the feedback linearization. The direct measurement of flux is practically difficult. Therefore, the voltage model of flux estimation has been preferred [6], where measurement of terminal voltage and stator current are required.

The α-β axis stator voltage vector component voltages are estimated as

$$V_{\alpha s} = -\frac{V_b}{\sqrt{3}} + \frac{V_c}{\sqrt{3}} \quad (21)$$

$$V_{\beta s} = \frac{2}{3}(V_a - \frac{V_b}{2} - \frac{V_c}{2}) \quad (22)$$

Similarly the α-β axis components of stator currents are estimated as

$$i_{\alpha s} = \frac{2}{3}(-\frac{\sqrt{3}}{2}i_b + \frac{\sqrt{3}}{2}i_c) \quad (23)$$

$$i_{\beta s} = \frac{2}{3}(i_a - \frac{i_b}{2} - \frac{i_c}{2}) \quad (24)$$

Where (V_a , V_b , V_c and i_a , i_b , i_c) are the sensed stator voltage and stator currents.

The α-β axis component of stator flux can be estimated by using the d-q component of stator voltages and currents.

$$\psi_{\alpha s} = \int (V_{\alpha s} - R_s i_{\alpha s})dt \quad (25)$$

$$\psi_{\beta s} = \int (V_{\beta s} - R_s i_{\beta s})dt \quad (26)$$

And the α-β component of rotor current referred to stator reference frame is obtained from the α-β component of stator fluxes and currents.

$$i_{\alpha r} = \frac{\psi_{\alpha s}}{L_m} - \frac{i_{\alpha s}}{L_m} L_s \quad (27)$$

$$i_{\beta r} = \frac{\psi_{\beta s}}{L_m} - \frac{i_{\beta s}}{L_m} L_s \quad (28)$$

Finally the α-β component of rotor flux is estimated by using the α-β component of rotor currents, stator currents and machine parameters.

$$\psi_{\alpha r} = L_r i_{\alpha r} + L_m i_{\alpha s} \quad (29)$$

$$\psi_{\beta r} = L_r i_{\beta r} + L_m i_{\beta s} \quad (30)$$

Where L_r and L_m are rotor self and magnetizing inductance respectively.

VII. DESIGN OF CURRENT CONTROLLER

By using park transformation three phase reference currents $i_a^*, i_b^* and i_c^*$ are obtained from $i_{\alpha s}^*$ and $i_{\beta s}^*$. The switching signal for the inverter devices is obtained by comparison of the motor currents (i_{as}, i_{bs}, & i_{cs}) with their reference counter parts ($i_{as}^*, i_{bs}^* \& i_{cs}^*$) . Hysteresis band with limits is properly selected by better performance of the current controller. The states of the devices are obtained in the following manner.

If $i_{as} \leq i_{as}^*$ – band limit then T_1 is on and $V_{an} = V_{dc}$

If $i_{as} \geq i_{as}^*$ + band limit then T_4 is on and $V_{an} = 0$

VIII. SIMULATION RESULT AND DISCUSSION

The proposed scheme with and without torque compensator is simulated in MATLAB simulink environment using Power system block set. Simulation results corresponding to speed response, torque response, stator current and rotor flux are presented corresponding to both the scheme. The results of the scheme are compared in Table-2.

From the point of view of starting time, reversal time, forward peak-up time, the proposed scheme with fuzzy compensator results in a better performance than the PI controller. It is found that the scheme with fuzzy torque compensator significantly reduces the torque ripple, as it appears with PI controller. Thus Fuzzy controller improves overall performance of the drive system. Author is of the view that the scheme with additional controller in the form of torque regulator compensator may be more suitable for a torque sensitive load example particularly low rating motor. Simulation results with feedback linearization reported in literatures [9] - [18] states at all levels complete decoupling has been achieved as shown in Fig.5 and Fig.6.

IX. CONCLUSION

The control for induction motor with feedback linearization and a torque compensator has been presented. The complete scheme is simulated in MATLAB simulink environment. The performance of the system is observed in terms of speed response, torque response corresponding motor current and flux. To demonstrate the effect of torque compensator /regulator the scheme is simulated without torque regulator also. The results obtained and compared and found that decoupling at all stages and there is reduction in the torque ripples and better rotor flux response when torque compensator is used.

TABLE 2: Comparative performance of proposed scheme with only PI and with fuzzy torque compensator

Input Signal	PI Controller	PI Controller with Fuzzy Torque Compensator
1. At t=0.00s, ω_r^* =500rpm, T_l=0Nm	Starting Time= 0.395 s	Starting time=0.37 s
2. At t=1.00 , T_l = 10 Nm	Speed deeps on load application rpm=0.35	Speed deeps on load application rpm=0.15
3. At t=1.50 s, T_l = 0 Nm	Speed rises to original value 500 rpm	Speed rises to original value 500 rpm
4. At t=2.00s, ω_r^* = - 500rpm, T_l=0Nm	Reversal Time=0.85 s	Reversal Time=0.72s
5. At t=3.00s , ω_r^* = 1000rpm, T_l =0Nm	Forward peak-up time =1.15s	Forward peak-up time =1.12s

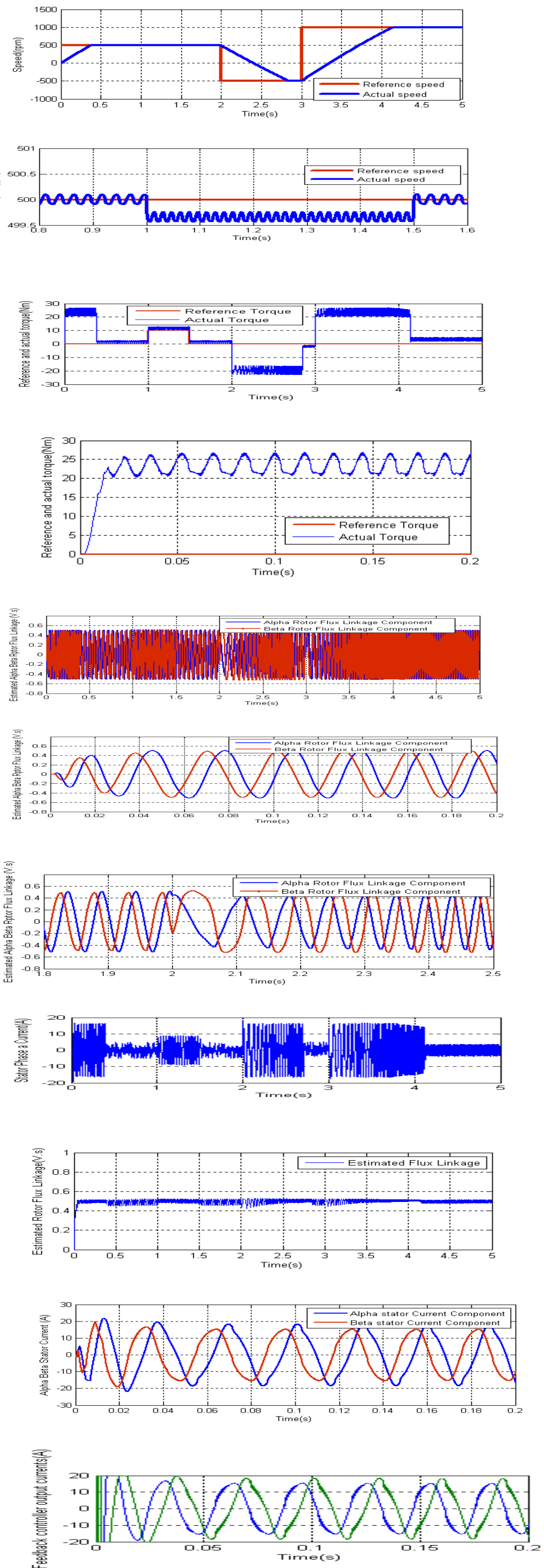

Fig.5. Simulation response for proposed scheme using PI controller

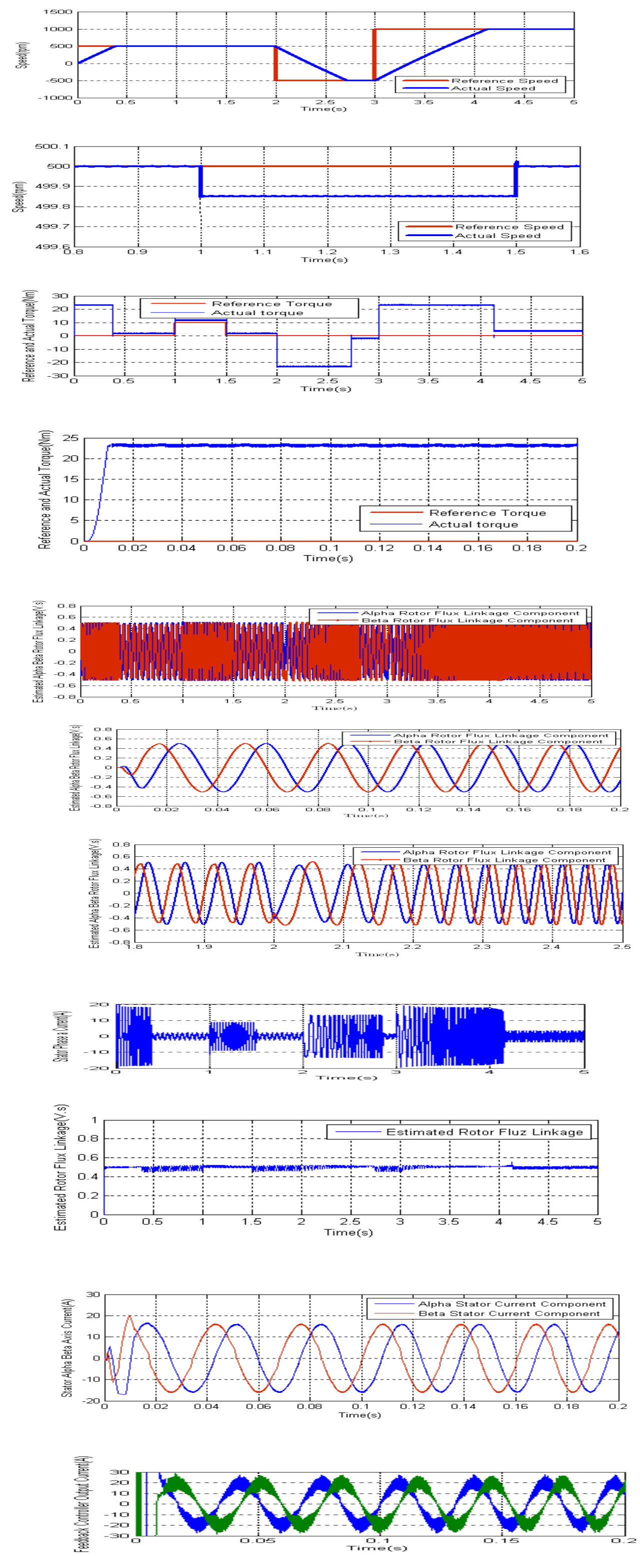

Fig.6. Simulation response for proposed scheme using PI controller and fuzzy torque compensator

X. APPENDIX

MOTOR SPECIFICATIONS

Three Phase Squirrel Cage Induction Motor – 5 HP (3.7 kW), 4 pole, Δ-connected, 415 V, 1445rpm, R_s = 7.34Ω, L_{ls} =0.021H, Lm =0.5H,R_r = 5.64Ω, L_{lr} = 0.021H, J=0.16Kg-m^2, B=0.035 Kg-m^2/s.

CONTROLLER SPECIFICATIONS

PI Flux controller : K_p = 1000, K_i= 500,

PI speed controller: K_p =10, K_i=0

With Fuzzy torque compensator

PI Flux controller: K_p= 1000, K_i= 500

PI speed controller: K_p= 10, K_i=1.9

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