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Genetic Algorithm Based Hybrid PID Fuzzy Speed Controller in FOCIM

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ABSTRACT

In this paper induction motor speed controlling using FOC with genetic algorithm tuned hybrid PID plus fuzzy controller is discussed. Tuning of PID plus fuzzy speed controller by GA improves static and dynamic performance of FOCIM. Nonlinear induction motor modeling is modeled as linear model for optimization of controller gains. Matlab/Simulink based simulations are carried out with different cases to check efficiency of proposed controller. These results are compared with conventional trial and error method to check improvement in peak overshoot and response time.

I. Introduction

Due to their flexibility in size, low maintenance and cost, high efficiency and reliability, induction motors are most commonly used in industrial applications [1]. Scalar and vector control are widely used speed controlling techniques of induction motor. V/Hz control is scalar open loop control and is useful for low performance applications [2]. Vector controlling is considered for high performance application which including field oriented control and direct torque control. Vector control is widely used and in this technique, torque and flux are controlled to achieve better speed tracking. Due to advanced technologies developed in power electronics and microprocessors efficient vector controlling techniques are developed for induction machine to reach smooth and hassle free performance [3]. By decomposing stator currents into torque and flux components field oriented control (FOC) controls the induction motor accurately. FOC is similar to DC motor controlling methods. To enhance efficiency of control process in FOC d-q based dynamic model of motor is used. Depending on rotor flux estimation FOC can be classified into indirect FOC and direct FOC [4, 5].

In Indirect FOC, four PI controllers are used in which 2 controllers are for inner current loop and one controller is for speed and one controller is for flux. To achieve appropriate static and dynamic performance accurate speed controller should be used [6].

Designing of speed controller is important in indirect FOC to get high performance and to decrease response time. Various methods are introduced previously which include deadbeat control, nonlinear control, fuzzy sliding mode control and artificial neural network control.

In [7], FOC with two sliding mode controllers is proposed. Main advantage of this system is fast dynamic performance, robustness and fast decoupling. In [8] and [9] fuzzy sliding mode control is proposed to reduce problems in sliding mode control built its computation time is large and complicated. Dead beat control is proposed in [10] which is having good dynamic and static performance. Main drawback of all these techniques is their complicated structure and difficulty in implementation.

Difficulty in tuning of PI and PID controllers for speed controlling leads to various complicated controlling methods. Due to relative robust performance controller simplicity and applicability PID controllers are used widely in various industrial applications [11]. Main difficulty arising in PID controller is tuning of their controller gains. Trial and error algorithm is used generally for FOC based induction motor. As range of search space for controller gains is not known, increases instability of system. Hybrid PID plus fuzzy controller further improves the performance of the system [12].

In this paper proposing a genetic algorithm based PID controller plus fuzzy for FOC based induction motor, to improve static and dynamic performance. Stability and performance of controller is investigated. PID controller gains are tuned using genetic algorithm for reducing peak overshoot and response time.

II. Induction Motor Model

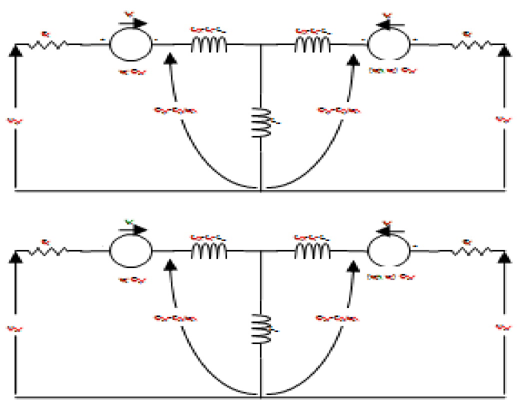

Fig 1. Induction Machine equivalent circuit in DQ frame.

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Krause's model is most popular model of induction motor detailed in [13]. DQ equivalent circuit of induction motor is shown in Fig. 1. Induction motor modeling equations in flux linkage form are given in equation 1-5 as

$$\frac{d\Phi_{qs}}{dt} = \omega_b\left[V_{qs} - \frac{\omega_e}{\omega_b}\Phi_{ds} + \frac{R_s}{x_{ls}}\left(\frac{x_{ml}^*}{x_{lr}}\Phi_{qr} + \left(\frac{x_{ml}^*}{x_{ls}} - 1\right)\Phi_{qs}\right)\right] \quad (1)$$

$$\frac{d\Phi_{ds}}{dt} = \omega_b\left[V_{ds} - \frac{\omega_e}{\omega_b}\Phi_{ds} + \frac{R_s}{x_{ls}}\left(\frac{x_{ml}^*}{x_{lr}}\Phi_{dr} + \left(\frac{x_{ml}^*}{x_{ls}} - 1\right)\Phi_{ds}\right)\right] \quad (2)$$

$$\frac{d\Phi_{qr}}{dt} = \omega_b\left[-\frac{(\omega_e-\omega_r)}{\omega_b}\Phi_{dr} + \frac{R_r}{x_{lr}}\left(\frac{x_{ml}^*}{x_{lr}}\Phi_{qs} + \left(\frac{x_{ml}^*}{x_{lr}} - 1\right)\Phi_{qr}\right)\right] \quad (3)$$

$$\frac{d\Phi_{dr}}{dt} = \omega_b\left[\frac{(\omega_e-\omega_r)}{\omega_b}\Phi_{qr} + \frac{R_r}{x_{lr}}\left(\frac{x_{ml}^*}{x_{ls}}\Phi_{ds} + \left(\frac{x_{ml}^*}{x_{lr}} - 1\right)\Phi_{dr}\right)\right] \quad (4)$$

$$\frac{d\omega_r}{dt} = \left(\frac{p}{2J}\right)(T_e - T_L) \quad (5)$$

R_s: Stator resistance, R_r: rotor resistance, X_{ls}: stator leakage reactance, X_{lr}: rotor leakage reactance, $X_{ml}^* = 1/\left(\frac{1}{x_m} + \frac{1}{x_{ls}} + \frac{1}{x_{lr}}\right)$, i_{ds}, i_{qs} : d and q axis stator currents, i_{dr}, i_{qr} : d and q axis rotor currents, v_{ds}, v_{qs} : d and q axis stator voltages, v_{dr}, v_{qr} : d and q axis rotor voltages, p : number of poles, J : moment of inertia, T_e : electrical output torque, ω_e : stator angular electrical frequency, ω_b : rotor angular electrical base frequency, ω_r : rotor angular electrical speed, $\Phi_{ds}, \Phi_{qs}, \Phi_{dr}, \Phi_{qr}$: stator and rotor direct axis and quadrature axis flux linkages.

III. Field oriented Control of Induction Motor

Due to superior dynamic performance of FOC, for AC drive, this control strategy for high performance of motor become the-trial standard. Fig. 8 shows the block diagram of FOC based induction motor drive. In FOC based IM drive total flux can be handled by d-axis, hence q-axis flux can be taken as zero.

$$\Phi_{qr} = 0 \quad (6)$$

$$\Phi_{dr} = \Phi_r \quad (7)$$

By using these values of flux in motor equations, FOC can be defined. The rotation slip speed is given as

$$\omega_{slip} = \frac{L_m R_r}{L_r \Phi_r} i_{qs} \quad (8)$$

And rotor flux is

$$\Phi_r = \frac{L_m}{\left(1+\frac{dT_r}{dt}\right)} i_{ds} \quad (9)$$

Φ_r is constant for FOC, from equations 1-5 reference stator current can be rewritten as shown in equations 10-14.

$$i_{ds}^* = \frac{\Phi_r^*}{L_m} \quad (10)$$

$$v_{ds} = \sigma L_s i_{ds} + \left(R_s + R_r\frac{L_m^2}{L_r^2}\right) i_{ds} - \omega_s \sigma L_s i_{qs} - \frac{L_m}{L_r^2} R_r \Phi_r \quad (11)$$

$$v_{qs} = \sigma L_s i_{qs} + \left(R_s + R_r\frac{L_m^2}{L_r^2}\right) i_{qs} - \omega_s \sigma L_s i_{qs} - \frac{L_m}{L_r^2}\omega_m \Phi_r \quad (12)$$

$$T_r \Phi_r^{\cdot} + \Phi_r = L_m I_{sd} \quad (13)$$

$$\omega_s = \omega_m + \frac{L_m}{T_r} . \frac{I_{qs}}{\Phi_r} \quad (14)$$

Inverter output voltages are chosen from decoupling control method as shown in equations 15-16

$$v_{ds}^* = \left(K_{p1} + K_{i1}\frac{1}{s}\right)(i_{ds}^* - i_{ds}) - \omega_e \sigma L_s i_{qs}^* \quad (15)$$

$$v_{qs}^* = \left(K_{p2} + K_{i2}\frac{1}{s}\right)(i_{qs}^* - i_{qs}) + \omega_e \sigma L_s i_{ds}^* + \omega_r \frac{L_m}{L_r}\Phi_{dr} \quad (16)$$

K_{p1}, K_{i1}, K_{p2} *and* K_{i2} are controller gains of PI1 and PI2. These gains are chosen by trial and error method such that error between reference current and actual current should be minimum. PI3 and PI4 are another two controllers to estimate reference currents to be required by induction motor stator to maintain reference speed and constant flux. Direct and quadtrature axis reference stator currents are derived as shown in equations 17-18.

$$i_{qs}^* = \left(K_{p3} + K_{i3}\frac{1}{s} + K_{d3}s\right)(\omega_m^* - \omega_m) \quad (17)$$

$$i_{ds}^* = \left(K_{p4} + K_{i4}\frac{1}{s}\right)(\Phi_r^* - \Phi_r) \quad (18)$$

K_{p3}, K_{i3} *and* K_{d3} are gains of PID controller which are to be tuned for effective speed tracking and to maintain minimum error between reference and actual speed. These gains are tuned by using genetic algorithm as the main objective of FOC is speed controlling.

IV. Robust PID controller

Block diagram of PID control is shown in fig 2. error signal between actual and reference value is the input for PID controller and output excitation signal is given as in equ. 19.

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{d}{dt}e(t) \quad (19)$$

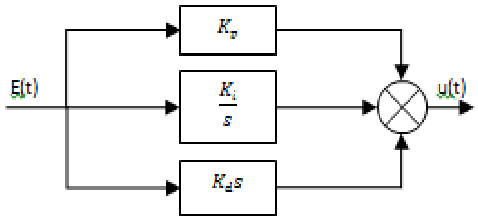

Fig 2. PID Controller.

in laplace transform equation 19 is written as

$$u(s) = e(s)\left(K_p + \frac{K_i}{s} + K_d s\right) \quad (20)$$

$$C(s) = \frac{u(s)}{e(s)} = \left(K_p + \frac{K_i}{s} + K_d s\right) \quad (21)$$

Discrete transfer function for $C(s)$ is given as

$$C(z) = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2}}{1 - b_1 z^{-1} - b_2 z^{-2}} \quad (22)$$

In digital system relation between PID gains and its implementation is shown in Table 1.

Table 1. PID gains relation

$C(z)$	a_0	a_1	a_2	b_1	b_2
$C(s)$	$K_p + K_i + K_d$	$-(K_p + 2K_d)$	K_d	1	0

For motor operation, parameters variation and nonlinear behavior of motor occurred because of heating and influence the resistance of rotor and stator. Multiple model approaches are used for modeling of uncertainty and non linear dynamics of induction motor. Response of induction motor can be divided into several parts from starting time to the time reaching steady state and can be derived each part into equivalent linear model. From motor equivalent equations, it is clear that this moor is a system of order 5 and it can be modeled by a linear transfer function with order 5 given in equation 23. [14]

$$IM\ transfer\ function = \frac{a_0 + a_1 s + a_2 s^2 + a_3 s^3 + a_4 s^4}{b_0 + b_1 s + b_2 s^2 + b_3 s^3 + b_4 s^4 + b_5 s^5} \quad (23)$$

Parameter uncertainty ranges are stated as follows

$a_i \epsilon [a_i^-, a_i^+], i = 0,1, \dots, 4.$

$b_i \epsilon [b_j^-, b_j^+], i = 0,1, \dots, 5.$

V. Genetic Algorithm

Genetic algorithm based on genetics is a powerful search and optimization algorithm derived by Prof. John Holland of University of Michigan. By searching for random set of solutions GA can be initiated. Search and optimization problem of each solution is related to fitness of objective function. By applying three genetic operators reproduction, crossover and mutation solutions population can be updated to new population. Modification of the population of solutions can be done iteratively till termination criterion reached [15]. Genetic algorithm can able to find optimal solution combinations for large search spaces. It is very different from traditional optimization methods. Traditional optimization methods use single point approach whereas GA uses population of solutions at a time. Flow chart for working process of GA is shown in fig 3. population of solutions can be updated for every iteration by three operators reproduction, crossover and mutation up to terminal condition is achieved. This representation is similar to natural chromosome and operators are similar to genetic operators hence this algorithm is called as genetic algorithm.

Reproduction is the process of selecting best individuals from present population to form part of the new population. Crossover operation creates new population from present individuals by using crossover probability. By selecting one or more crossover points from each parent at the same place new population can be generated. Mutation modifies selected individuals by using mutation probability. Mutation operator creates new individual by mutating selected part of selected chromosome. Value of mutation probability should be chosen moderate as in case of large value GA is purely stochastic approach, and too small value face difficulty to create population.

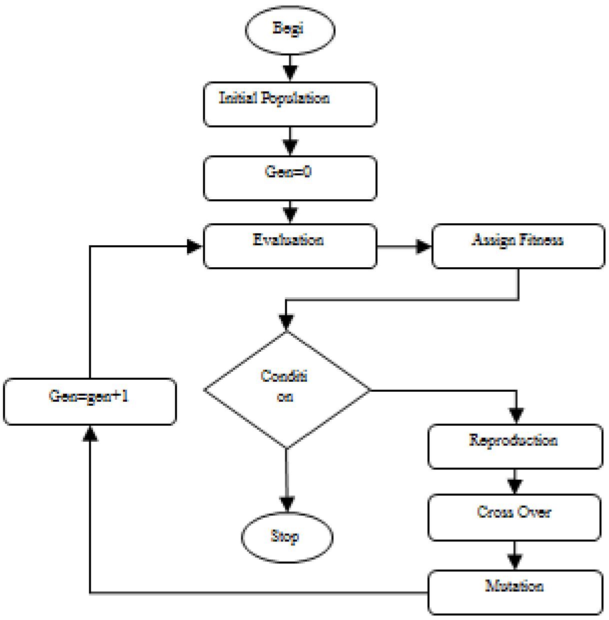

Fig 3. Flow chart of genetic algorithm.

Population of GA should be evaluated to get optimal solution for a function f. By minimizing and maximizing objective function J, each individual fitness value can be calculated.

$$f = 1/J \tag{24}$$

Each individual is tagged as best and worst by using fitness value. For every generation of optimization process optimal solution is obtained by selecting best individuals. Each generation include generation of population, application of genetic operators on it and evaluation of population. Iteration will be finished once terminal criterion reached. Selection and crossover operators exploit the search space and mutation operators explore the search space for new population for GA's better convergence.

Implementation of GA is as follows

1)Initial generation of individual chromosomes with fixed size randomly. Each chromosome in these is a possible solution. As these chromosomes are chosen randomly, the system may become unstable. Hence the range of the chromosomes should be such that system remains stable.

2)By using initial chromosome of the population, calculate fitness of objective function.

3)Select the chromosomes of the population which are minimizing objective function.

4)Reproduce the population by probabilistic method

5)Crossover operation on these reproduced chromosomes

6)Mutation operation

7)Repeat from step 2 until termination criterion reached

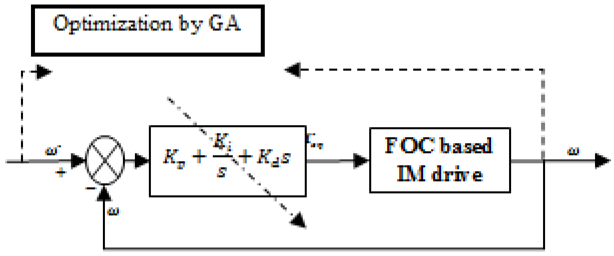

Fig 4. Optimization of PID controller using GA.

Structure of optimization of PID controller gains for FOC based IM drive is shown in fig 4. transfer function of IM and FOC drive is taken as fitness function for optimization. Main objective of optimization of PID controller gains is to achieve less settling time, small over shoot and fast rise time in speed tracking.

VI. Hybrid PID plus fuzzy controller

Controller structure of the hybrid PID plus fuzzy controller is shown in fig 5. PID controller is tuned by genetic algorithm. In proposed system output of PID controller is the input to fuzzy controller which further improves speed tracking. Three input membership functions $m_N(x)$, $m_Z(x)$ and $m_P(x)$ are taken for input crisp value to map it with fuzzy set with a degree of certainty. Only three member ship functions are chosen for input as to reduce complexity of computation. For any $x\epsilon N$, $N = [-\infty, 0]$ linguistic variable is 'N', any $x\epsilon Z$, $Z = [-b, b]$ linguistic variable is 'Z' and any $x\epsilon P$, p= $[0, \infty]$ linguistic variable is 'P' [16].

By using adequate IF-THEN rules in knowledge base for decisions, input fuzzy sets in combination produces an output fuzzy set. For this application IF-THEN rules are given as in table 2. Membership functions are shown in fig **7.**

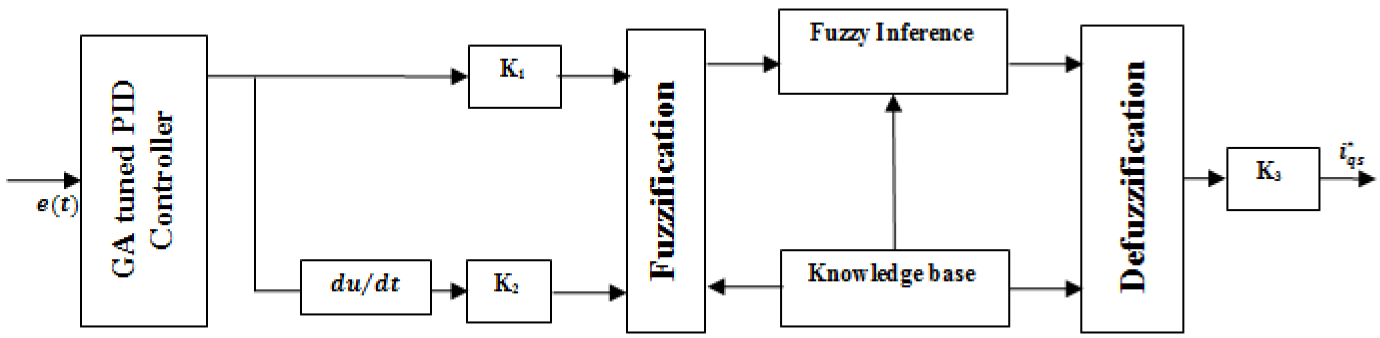

Fig 5. Hybrid PID plus fuzzy controller.

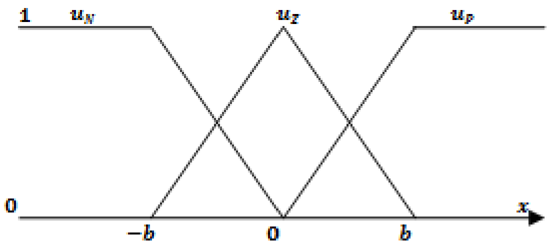

Fig 6. Membership functions for inputs and output.

In defuzzification process center of mass defuzzification is employed and fuzzy set output will be transformed into crisp output.

VII. Simulation Results

Using MATLAB/SIMULINK simulations are carried out to check the effectiveness of proposed tuning algorithm for PID controller in FOC. Parameters of the induction motor used in the simulation are given in table II. Block diagram of FOC is shown in fig 8.

Three different cases are considered in simulation to compare normal PID tuned by trial and error method with GA tuned PID controller. Cases are 1. Load increase, 2. Speed reversal, 3. Change in speed.

Table II. Fuzzy rule Base

$\Delta u(t)$ $u(t)$	N	Z	P
N	b	b	b
Z	-b	0	b
P	-b	-b	-b

a. Load increase

Reference speed of 1500 RPM is given and load torque is increased from 0 to 15 Nm between 2-3 sec. actual and reference speed is shown in fig 7. Response time of speed to reach reference value is 0.2 seconds in case of normal PID. Peak over shoot in case of normal PID is reached 1750 RPM. Speed tracking is not affected even during load increase. Stator currents are shown in fig 9. To withstand increase in load stator currents magnitude is also increased during 2-3 sec. stator currents during speed increase and load increase are shown in fig 10 and 11. Response of electromagnetic torque is shown in fig 12. High ripples in torque affecting the stator currents waveform by increasing total harmonic distortion.

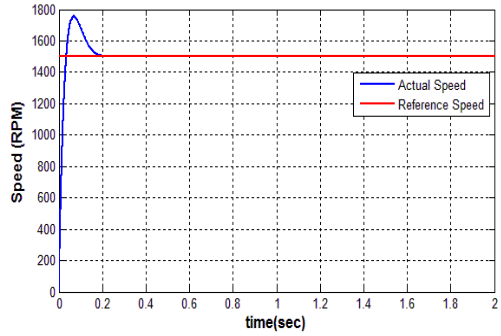

Fig 7. Actual and reference speed with normal PID

Table III. Parameters of Induction motor .

Stator Resistance	17 Ω
Stator Leakage Reactance	0.196 H
Rotor Resistance	17 Ω
Rotor Leakage Reactance	0.196 H
Magnetizing Inductance	1.88e-3 H
Moment of Inertia	2.4e-4
No. of poles	4

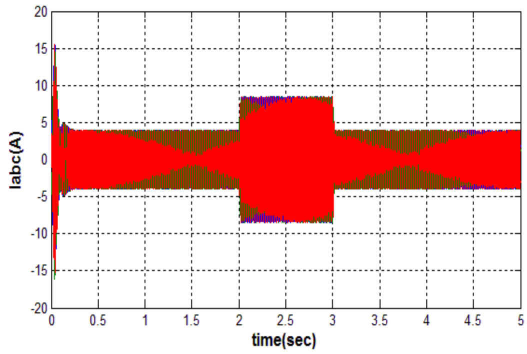

Fig 9. Stator currents with normal PID.

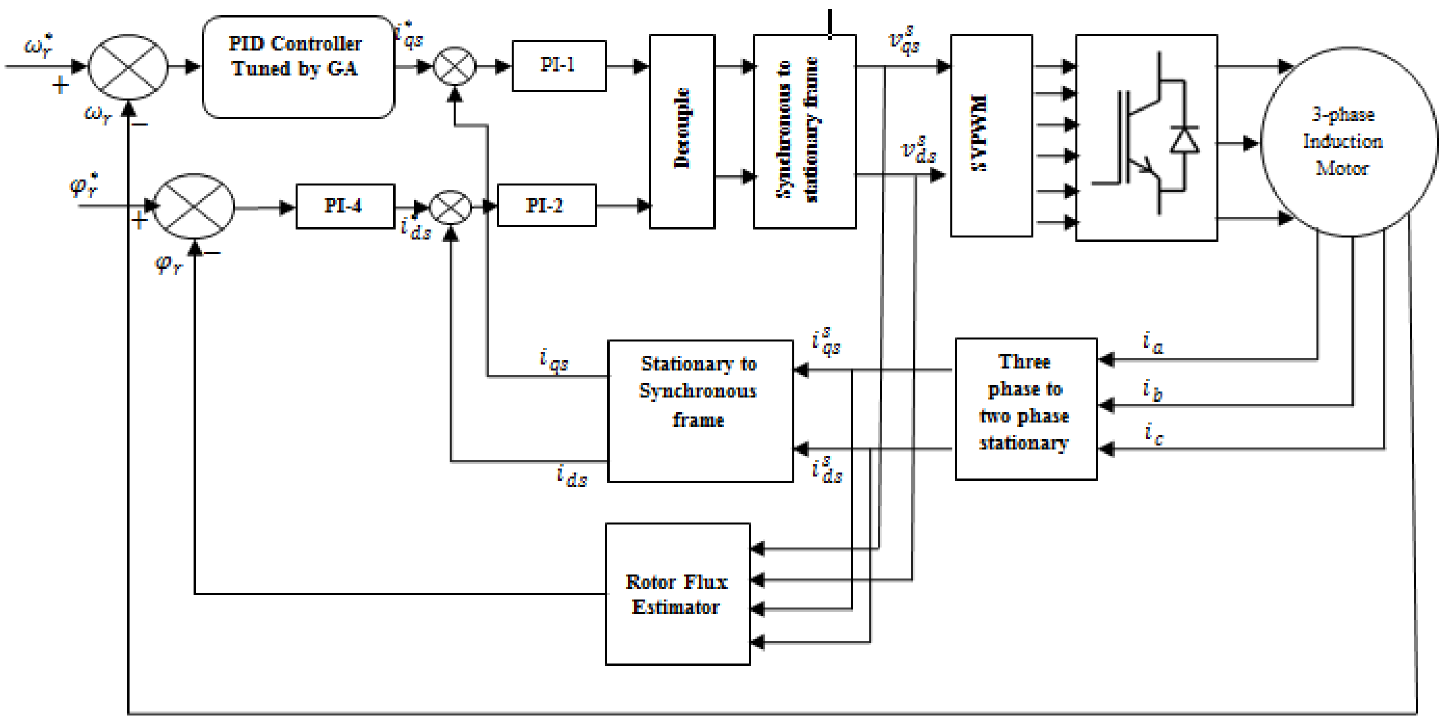

Fig 8. Field Oriented Control.

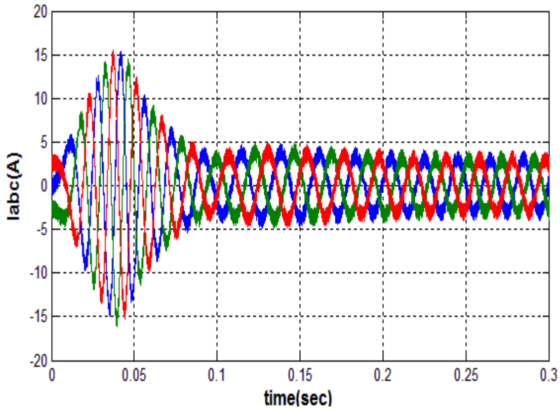

Fig 10. Stator currents during speed increase.

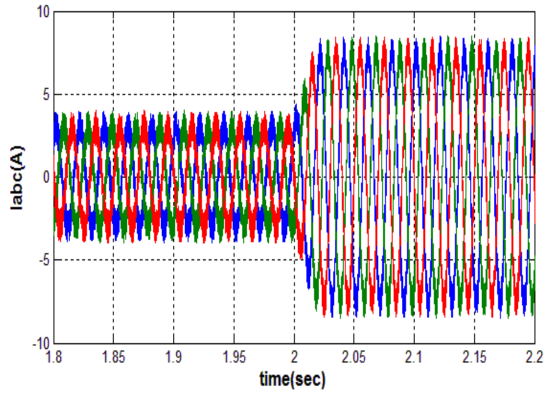

Fig 11. Stator currents during sudden load increase.

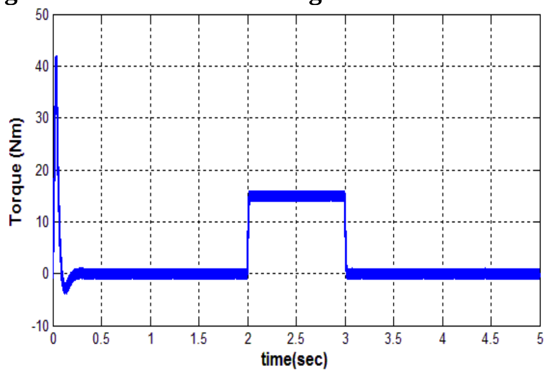

Fig 12. Electro magnetic torque of IM with normal PID during load increase.

Speed response with GA tuned PID controller is shown in fig 13. Speed response time is reduced from 0.2 seconds to 0.1 second and peak overshoot is also reduced to 1540 RPM. Stator currents are shown in fig 14-16. Response of electromagnetic torque with GA tuned PID is shown in fig 17. As ripples in torque waveform are very less, harmonics in stator currents are also reduced in GA tuned PID.

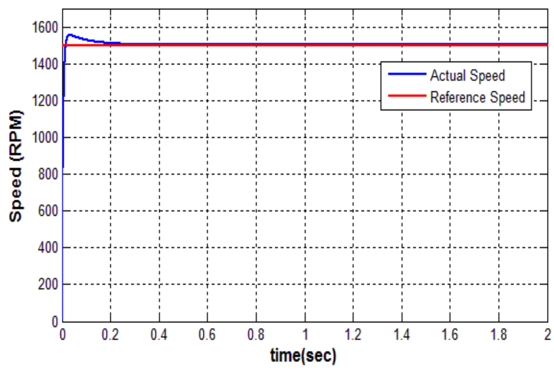

Fig 13. Actual and reference speed with GA tuned PID.

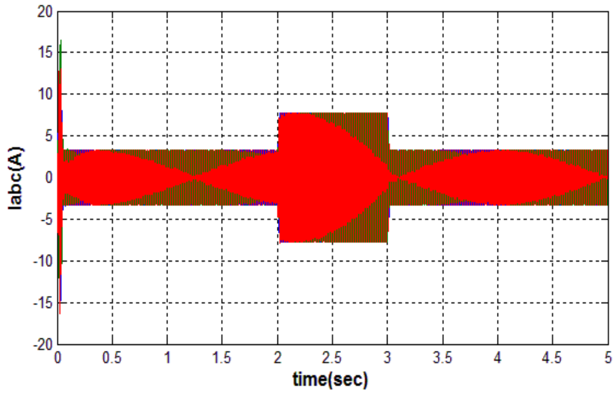

Fig 14. Stator currents with GA tuned PID.

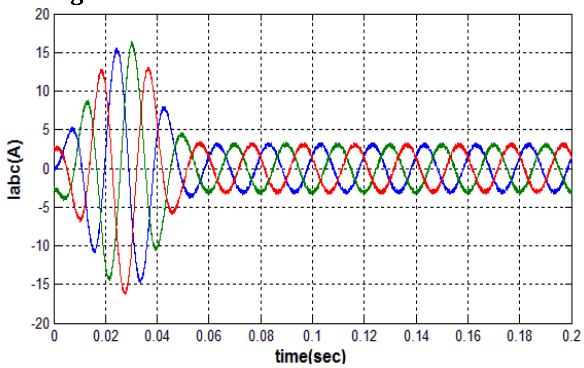

Fig 15. Stator currents during speed increase.

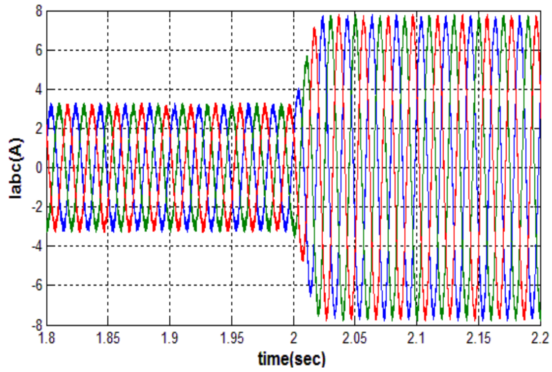

Fig 16. Stator currents during sudden load increase.

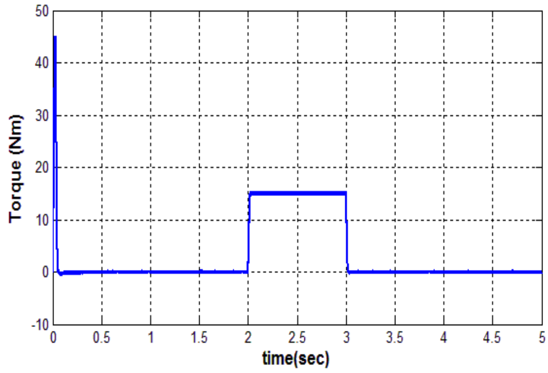

Fig 17. Electro magnetic torque of IM with GA tuned PID during load increase.

b. Speed Reversal

Response of FOC during speed reversal with normal PID is shown in fig 18-21 and with GA tuned PID is shown in 22-24. Until three seconds reference speed is maintained constant at 1500 RPM and at 3 seconds speed starts decreasing and reversed then reached -1500 at 4 seconds. Peak over shoot, response time, torque ripples and hence harmonics in stator currents are less in GA tuned PID compared to normal PID

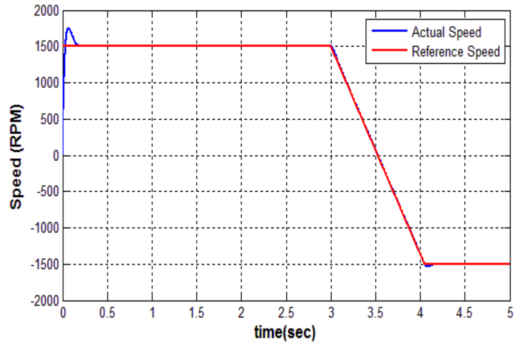

Fig 18. Actual and reference speed with normal PID during speed reversal.

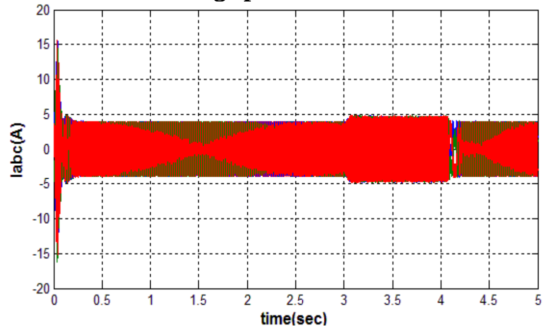

Fig 19. Stator currents with normal PID.

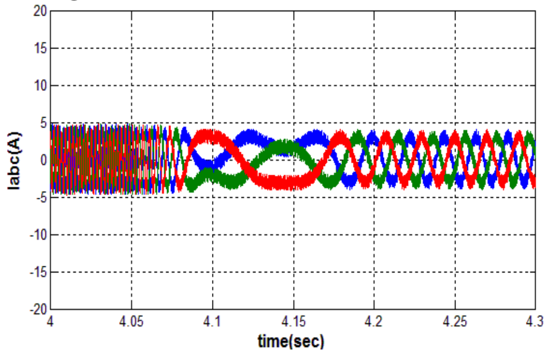

Fig 20. Stator currents during speed reversal.

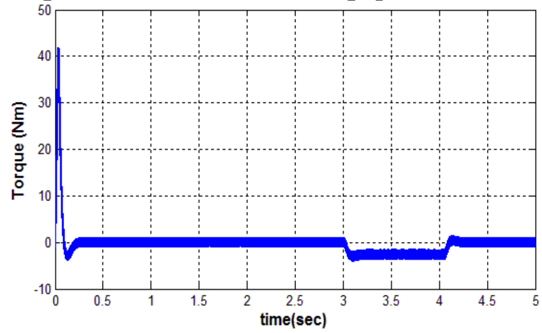

Fig 21. Electro magnetic torque of IM with normal PID during speed reversal.

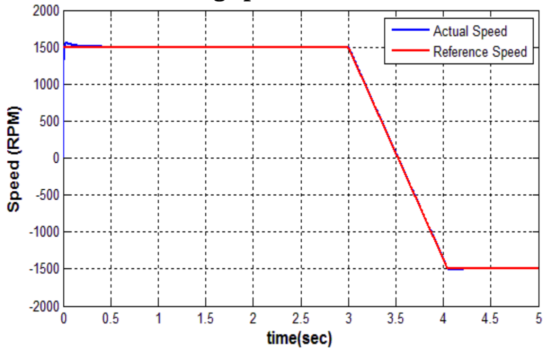

Fig 22. Actual and reference speed with GA tuned PID.

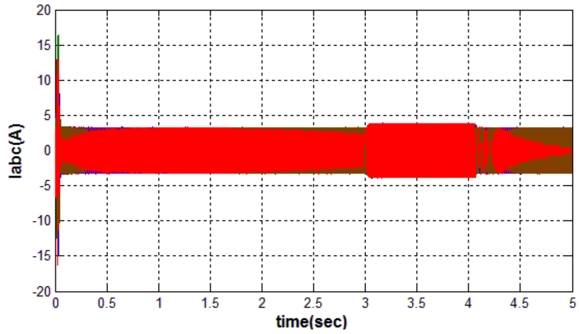

Fig 23. Stator currents with GA tuned PID.

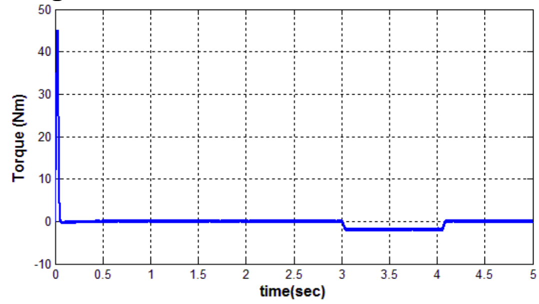

Fig 24. Electro magnetic torque of IM with GA tuned PID during speed reversal.

c. Change in speed

In this case a sudden change in reference speed is considered. Initial ref speed is 500 RPM then at 1sec, 2sec, 3 sec speed is increased to 1000, 1200 and 1500 RPM respectively. Fig 25-27 are response of normal PID and fig 29-31 are response of system with GA tuned PID.

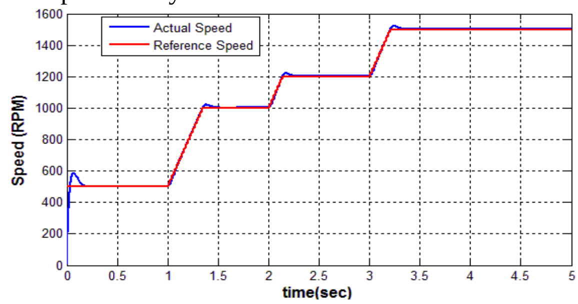

Fig 25. Actual and reference speed with normal PID during speed change.

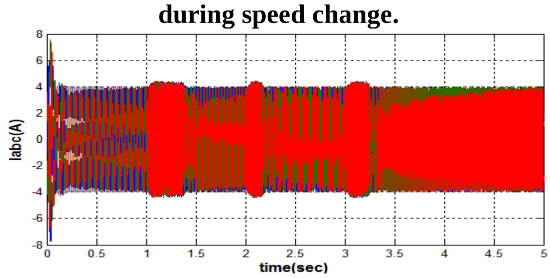

Fig 26. Stator currents with normal PID.

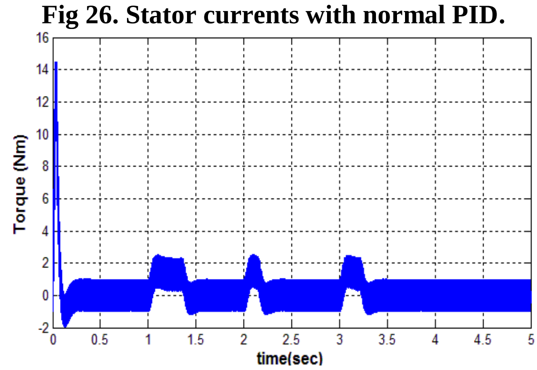

Fig 27. Electro magnetic torque of IM with normal PID during speed change.

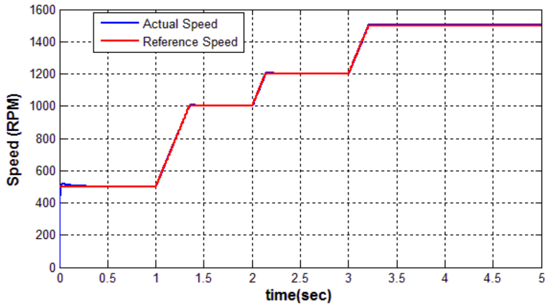

Fig 28. Actual and reference speed with GA tuned PID during speed change.

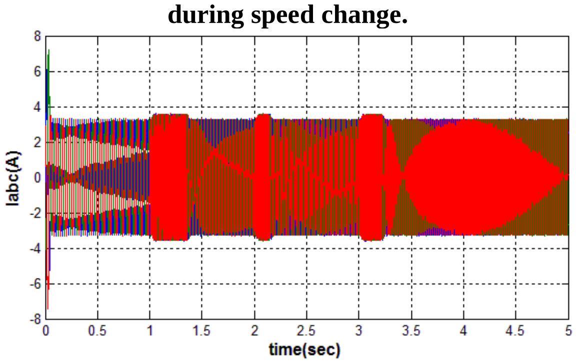

Fig 29. Stator currents with GA tuned PID.

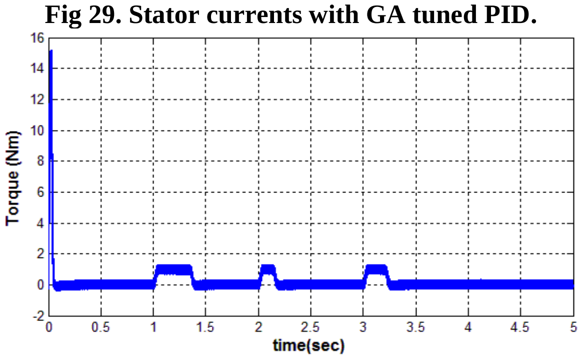

Fig 30. Electro magnetic torque of IM with GA tuned PID during speed change.

VIII. Conclusion

FOC based induction motor with hybrid PID plus fuzzy controller optimized by genetic algorithm is proposed. Non linear induction motor is modeled as uncertain linear model. Controller gains of PID optimized with genetic algorithm using induction motor model. Matlab/Simulink based simulations are carried out and proposed algorithm is compared with conventional trial and error method. In genetic algorithm optimized PID peak overshoot is reduced and response time is improved as compared to conventional method.

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