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PI Controller and Fuzzy Logic Controller based Loss Minimization Techniques for Induction Motor Drives

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ABSTRACT: This paper presents loss minimization techniques for a variable speed, three-phase, squirrel-cage, indirect vector controlled induction motor drive that minimizes total losses and optimizes efficiency through optimal control using proportional plus integral (PI) and fuzzy logic controller. Loss minimization is obtained by proper designing of appropriate controller. Three phase stator current of an induction motor with d-q co-ordinates is referred to the hysteresis band current controller for pulse width modulation. This transformation results in reduction of output voltage obtained from the three phase voltage source inverter and applied to the stator input terminals of induction motor drive, thus the decomposition into d-q components in the steady-state motor model can be utilized in deriving the reduced motor losses. The drive system is simulated using Matlab/Simulink models and simulation results based on total losses and efficiency are compared with changing load torque.

KEYWORDS: Fuzzy logic, PI controller, loss minimization, efficiency optimization, induction motor drive.

I. INTRODUCTION

The importance of the loss minimization for the induction motor drives may be realized from different perspectives because as far as the energy consumption is concerned the electric motors consume more than 50% of the electrical energy produced. Of this, the major share goes to induction motors, the main workhorse of industry. Also, they are most widely used in electrical drives because of their robustness, ruggedness, reliability and low cost. Despite of many advantages of induction motor there are some disadvantages also. Like it is not true constant speed motor, slip varies from less than 1% to more than 5%. Also it is not capable of providing high efficiency and low losses. But as it is so useful for industries we have to find some solution to solve these limitations and the solution is loss minimization controller that can take necessary action to reduce motor losses [1]-[2]. Not only reduce losses, but it can control various parameters of the induction machine such as flux, torque, voltage, stator current [4]. Out of the several procedures for loss minimization of an induction motor drive, voltage reduction when the motor is operating with light load is found to be the effective method used for obtaining reduced power losses [6]. In general, electrical motor drive contains losses like converter loss, motor loss and transmission loss. Thus in an effort to minimize the loss and improve efficiency of induction motor drive with different techniques, design and construction of some loss minimizing ideas are needed. This work presents a loss minimization model based techniques of induction motor drives. The efforts on loss minimization can be done through improved design of motor and converter by introducing better control techniques with the best result.

II. LOSSES IN INDUCTION MOTOR DRIVE

The process of energy conversion within motor drive leads to the power losses in the motor windings and magnetic circuit as well as conduction and commutation losses in the inverter.

Motor losses

Motor losses consist of hysteresis and eddy current losses in the magnetic circuit (core losses), losses in the stator and rotor conductors (copper losses) and stray losses. At nominal operating point, the core losses are typically 2-3 times smaller than the copper losses, but they represent main loss component of a lightly loaded induction motor drives. Copper losses are due to flow of the electric current through the stator and rotor windings. The stray flux losses depend

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on the form of stator and rotor slots and are frequency and load dependent. The total secondary losses (stray flux, skin effect and shaft stray losses) usually don't exceed 5% of the overall losses. Considering that the stray losses are of importance at overload conditions, while the efficiency optimizer is effective at light load, the stray losses are not considered as a separate loss component in the loss function.

III. LOSS MINIMIZATION

Loss minimization is inversely proportional to the efficiency maximization. The efficiency of electrical machines depends on the type, size and quotient of partial load over rated load. Improvement of the efficiency can be obtained with the following methods:

1. Reduction of size (replacement of the motor), when the motor permanently operates in an area of partial load.
2. Voltage reduction, when the motor is operating with light load.
3. Improvement of power factor of lightly loaded induction motor by reducing the stator voltage.
4. V/f ratio is kept constant which in turns maintains the magnetizing flux constant that eliminates harmonics problem and maximum torque also does not change.

IV. INDIRECT VECTOR CONTROL SYSTEM

Indirect vector control principle was introduced by Blaschke in 1972. It states that the flux and torque can be controlled independently. It consists of dynamic d-q model which consists of voltage source inverter, flux calculation, theta calculation, current and voltage sensing elements. Fig. 1 shows a d-q model for indirect vector control system. Usually, a vector control technique provides the application of induction motor drives for improved and high performance. Indirect vector control system is somewhat similar as that of direct vector control except that the rotor angle θe is generated in an indirect manner using the measured speed ω_r and slip speed ω_{sl}. Following dynamic equations are necessary to be take into consideration for the implementation of indirect vector control strategy.

The induction motor drive is fed by a 3 phase 6 step voltage source PWM inverter. In case of PI controller, the motor speed ω_r and steady state error is produced is given to the speed controller. The output of PI controller generates a reference command in the form of electromagnetic torque Te^*. While considering the case of Fuzzy logic controller, the steady state error is introduced by comparing the slip and efficiency as the input to the controller. It generates the reference command in the same way as that of PI controller in the form of T_e^*.

The quadrature axis stator current reference is calculated by,

$$i_{qs}^{*} = \frac{2}{3}\frac{2}{P}\frac{L_r}{L_m}\frac{T_e^{*}}{\hat{\psi}_r} \tag{1}$$

where $\hat{\psi}_r = |\psi_r|_{est.}$ is the estimated value of rotor flux given by,

$$\hat{\psi}_r = \frac{L_m . i_{ds}}{1+\tau_r . s} \tag{2}$$

where, $\tau_r = \dfrac{L_r}{R_r}$ is the rotor time constant.

The direct axis stator current reference i_{ds}^{*} obtained from rotor flux input $|\psi_r|^{*}$,

$$i_{ds}^{*} = \frac{|\psi_r|^{*}}{L_m} \tag{3}$$

The rotor flux position θ_e required for co-ordinates transformation is obtained from the rotor speed ω_r and slip speed ω_{sl} is calculated as

$$\theta_e = \int \omega_e dt = \int (\omega_r + \omega_{sl}) dt = \theta_r + \theta_{sl} \tag{4}$$

The slip speed ω_{sl} is calculated from the stator reference current i_{qs}^{*} and the motor parameters, given by

$$\omega_{sl} = \frac{L_m . R_r}{\psi_r . L_r} i_{qs} \tag{5}$$

The electromagnetic torque is,

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\psi_r . i_{qs} \tag{6}$$

The i_{qs}^{*} and i_{ds}^{*} current reference are converted into phase current references i_a^{*}, i_b^{*} and i_c^{*} using inverse park transform (dq-abc) and fed to the hysteresis band current controller. The controller processes the measured and reference currents to produce inverter gating signals.

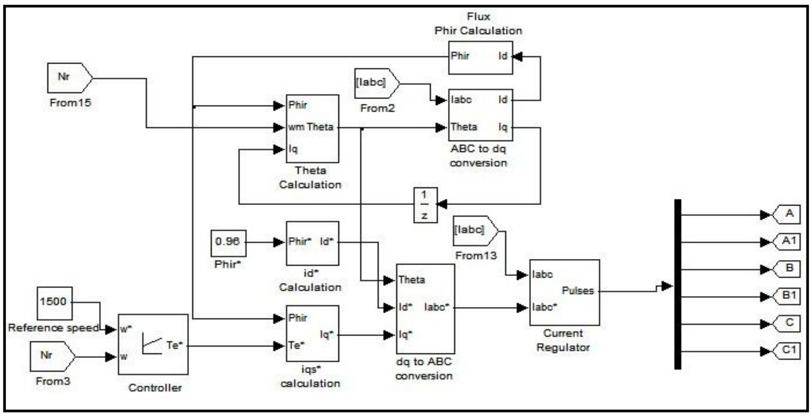

Fig. 1.d-q model for indirect vector controlled drive

V. THE APPLIED CONTROL STRATEGY

1. Proportional plus integral (PI) controller

The first technique adopted in this paper is by using PI controller. The PI controller is a device that produces an output signal which is proportional to the input signal. It improves the steady state tracking accuracy, disturbance signal rejection and relative stability. It also decreases the sensitivity of the system to the variation in parameters. The PI controller produces an output signal consisting of two value- one proportional to the input signal and other proportional to the integral of input signal. The concern of PI controller in the system is to reduce the speed loop error and increase the order and type of the system by one as shown in Fig. 2.

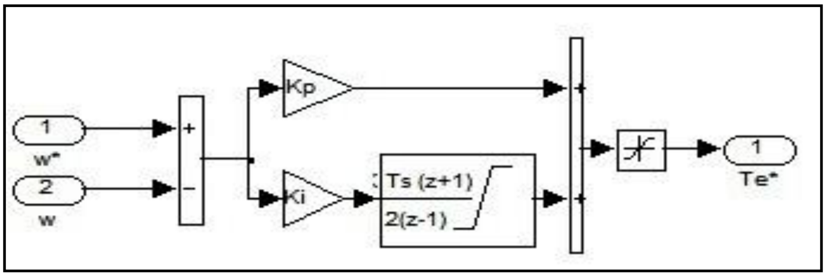

Fig. 2.PI controller

The main role of the PI controller is to keep rotor speed equal to the reference speed input in steady state by allowing both the inputs passing through PI regulator and limiter. It also provides close loop current control which operates the voltage source inverter in current control mode whose switching is made in such a way that it produces the reduced value of rms voltage fed to the stator input terminals of induction motor. This reduces the three phase stator current which in turns reduces the input power of the motor as compared to the power obtained without controller. This further reduces the total losses obtained on the rotor side improving the efficiency. Table 1 shows the values of total losses and efficiency obtained at changing load torque (N-m). Fig. 3 and Fig. 4 shows the stator voltages while Fig. 5 and Fig. 6 shows the stator currents waveforms without controller and with PI controller respectively.

The total power losses,

$$\sum \Delta P = P_{in} - P_{out} \tag{7}$$

$$\therefore \sum \Delta P = W_{Total} = Losses_{Total} = \frac{3}{2}\left(v_{qs}.i_{qs} + v_{ds}.i_{ds}\right) - T_e.\omega_r \tag{8}$$

Efficiency of the induction motor is given by

$$\eta = \frac{T_e.\omega_r}{T_e.\omega_r + W_{Total}} \tag{9}$$

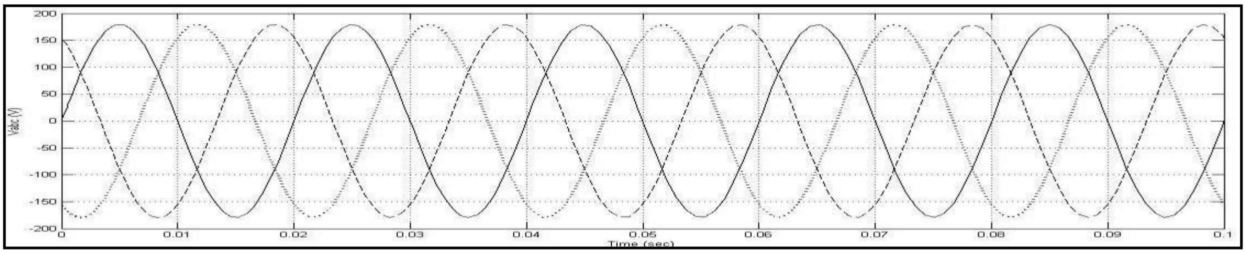

Fig. 3.Three phase stator voltage obtained without controller

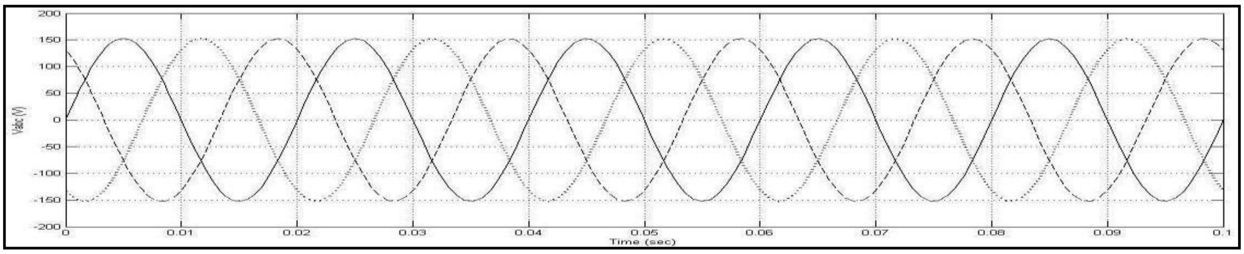

Fig. 4.Three phase stator voltage obtained with PI controller

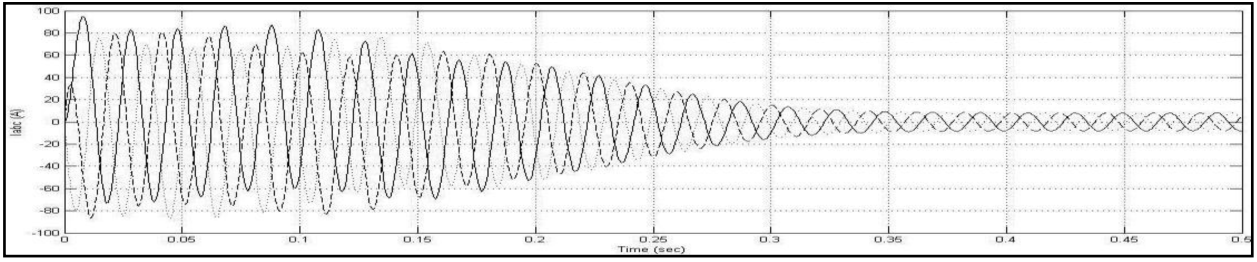

Fig. 5.Three phase stator current obtained without controller

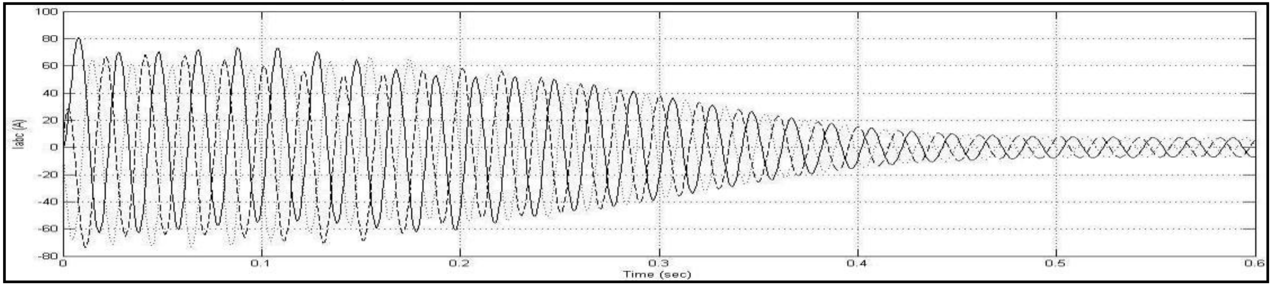

Fig. 6.Three phase stator current obtained with PI controller

2. Fuzzy Logic Controller (FLC)

In other proposed control strategy, a fuzzy logic controller technique is used. It is made on the basis of nine rules fed into fuzzy set with two inputs and one output by proper modelling most of the parameters of induction motor (Stator and Rotor) and losses are taken under consideration. The simulation results are studied and taken for comparison in relation to their rotor speed of response, pulsation in torque and level of loss reduction and efficiency improvement. Fuzzy logic is a technique to inculcate human-like thinking into a control system. Hence, the main purpose of designing fuzzy controller is to embody the human intelligence or human like thinking in the controller to control the process parameters. To emulate human deductive thinking we design Fuzzy logic controller, that is, the process people use to infer conclusions from what they know. FLC has been primarily applied to the control of processes through fuzzy linguistic descriptions.

In a motor control system, the function of FLC is to convert linguistic control rules into control strategy based on heuristic information or expert knowledge. FLC approach is very useful for induction motor drives since no exact mathematical model of the induction motor or the closed-loop system is required. FLC has a fixed set of control logic rules, usually derived from the knowledge of experts. The membership function (MF) of the associated input and output linguistic variables is generally predefined on a common universe of discourse. For the successful design of FLC proper selection of input and output or tuning of the other controller parameters provides crucial jobs, which in several cases are done through trial and error to achieve the best possible control performance. For designing a fuzzy logic based controller, first thing we have to decide is what will be the inputs. As our main aim is to provide constant speed during load changes so the variable to be controlled will be speed.

The slip and efficiency are given as input to the fuzzy controller. The fuzzy logic controller initially converts the slip and efficiency in displacement into fuzzy variables; then they are mapped into linguistic labels. Membership functions are defined within the normalized range (-1, 1), and associated with each label: Low, Med (medium) and High. Three MFs are chosen for slip and efficiency signals and three for output. All the MFs are symmetrical for positive and negative values of the variables. Thus, maximum 3x3 = 9 rules can be formed. The membership function for the inputs (error slip and efficiency) and output of fuzzy controller are shown in Fig. 7, 8 and 9 respectively.

Fig. 11 and Fig. 12 shows the stator voltage (V_{abc}) and stator current (I_{abc}) waveforms obtained by applying Fuzzy logic controller. The values on both the waveforms are of reduced magnitude which affects the performance improvement in deriving low losses and optimized efficiency at changing load torque.

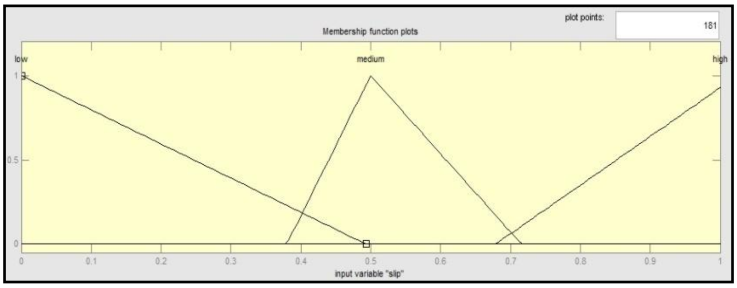

Fig.7.Slip membership function

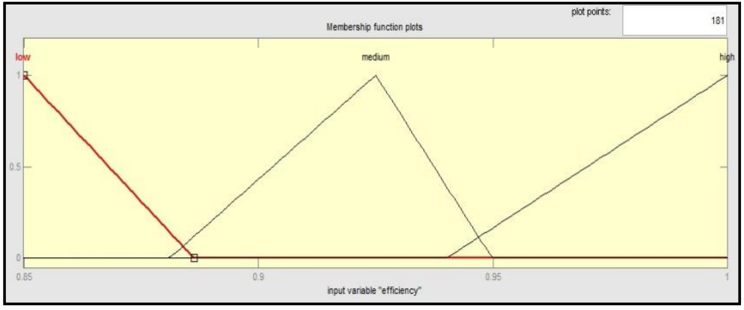

Fig.8.Efficiency membership function

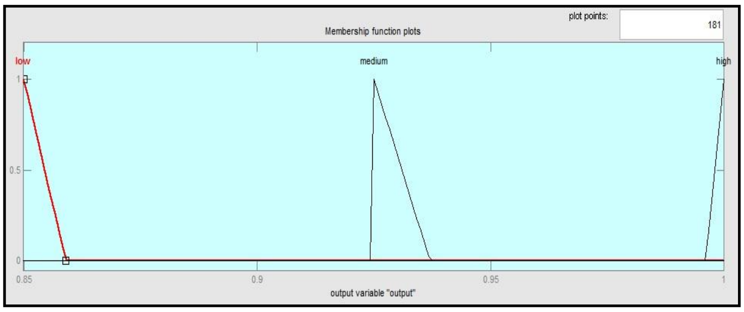

Fig.9.Output membership function

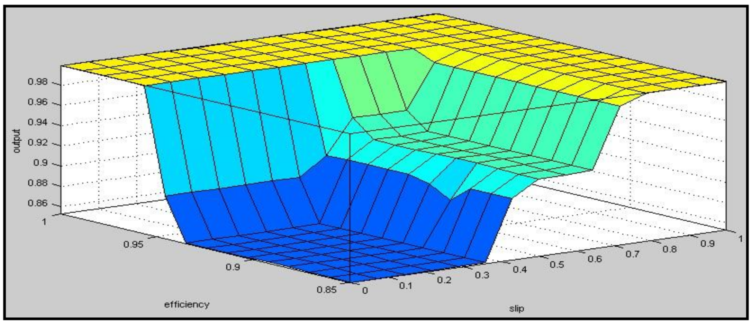

Fig. 10.Input and output surface for fuzzy inference module

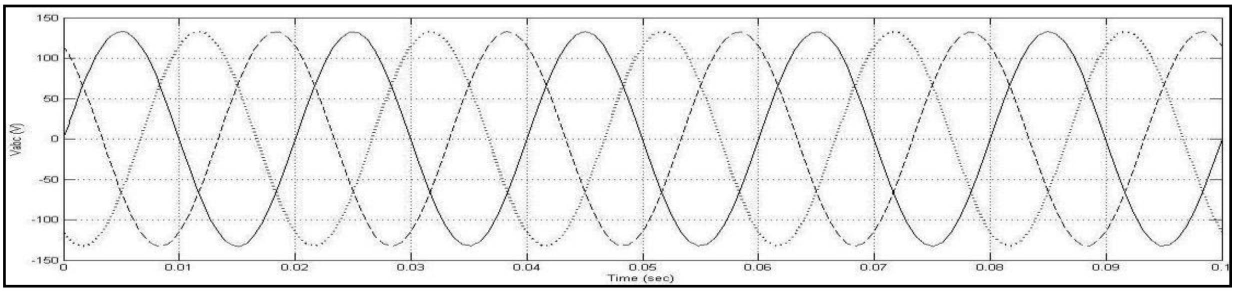

Fig. 11.Three phase stator voltage obtained with Fuzzy controller

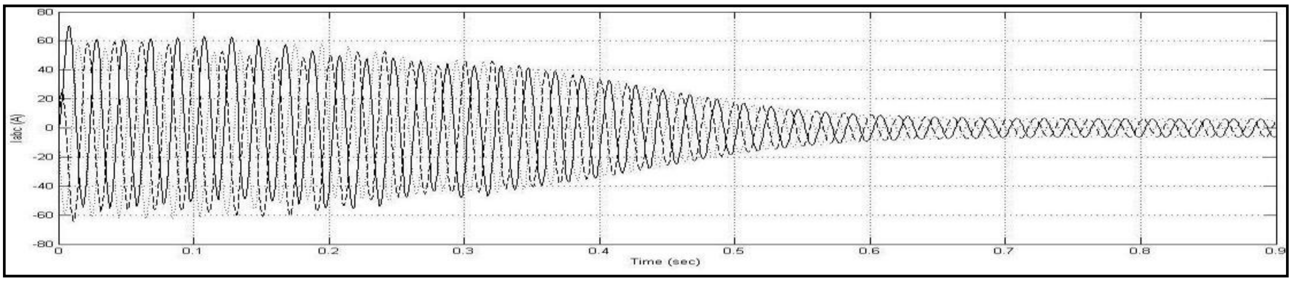

Fig. 12.Three phase stator current obtained with Fuzzy controller

VI. PULSE WIDTH MODULATION

There are various pulse width modulation techniques used for several applications. Some of which are third harmonic injection control, space vector pulse width modulation, sinusoidal pulse width modulation (SPWM), hysteresis band current controller. In this paper, hysteresis band current controller technique is used for proper switching of voltage source inverter.

Hysteresis Band Current Controller

The main aim of PWM technique is to generate output voltage with maximum fundamental component and minimum harmonics. Hysteresis band current controller has fast response of current loop and good accuracy. It does not require any knowledge of system parameters. It is an instantaneous feedback current controller in which command current is continuously tracked by the output current within pre-assigned hysteresis band. The switching logic is formulated as follows:

If $I_{abc} < I_{abc}^*$, upper switch is turned ON and lower switch is OFF.

If $I_{abc} > I_{abc}^*$, upper switch is turned OFF and lower switch is ON.

The bandwidth of the hysteresis band current controller determines the allowable current shaping error. By reducing the bandwidth the user can increase the inverter operating frequenncy with improved harmonic wave quality. But it will increase switching losses. The hysteresis band current controller scheme is shown in Fig. 13.

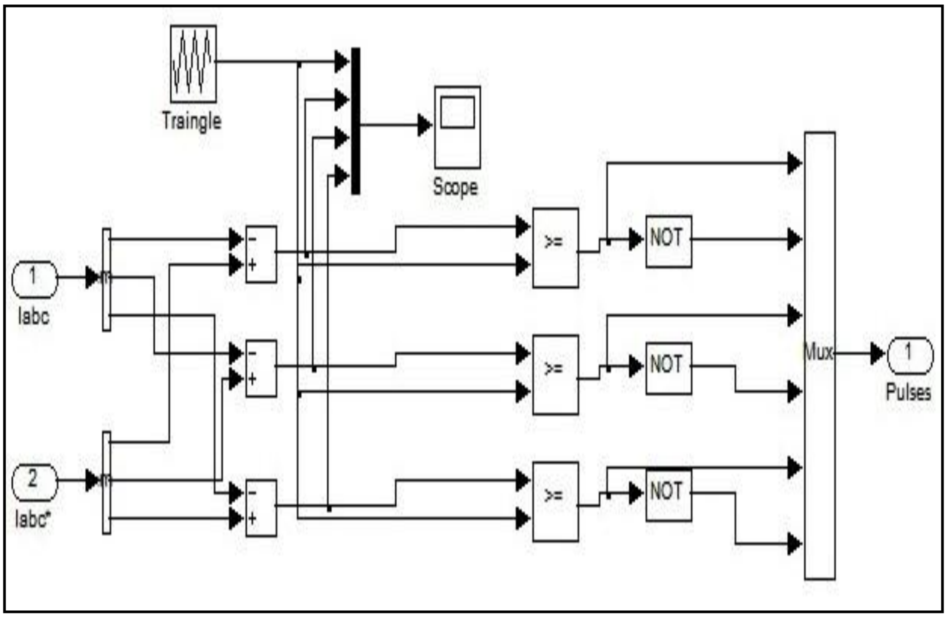

Fig. 13.Hysteresis band current controller

VII. SIMULATION RESULTS

Simulation studies are performed to validate a theoretical development. Simulation model is made in Simulink/Matlab software. Model of PI and Fuzzy logic controller incorporated in the model of induction motor drive are shown in Fig. 14 and Fig. 15 respectively. Power losses and efficiency of drive has been tested with both PI and Fuzzy logic controller and compared with the case when no controller is included in a drive model. Figures 16-19 shows the rotor speed (rpm), electromagnetic torque (N-m), efficiency and total power losses (W) at ¼ of full load torque (11.87 N-m) respectively while Table 1 shows the results displaying total losses and efficiency obtained with and without controller for the motor specifications given in Appendix.

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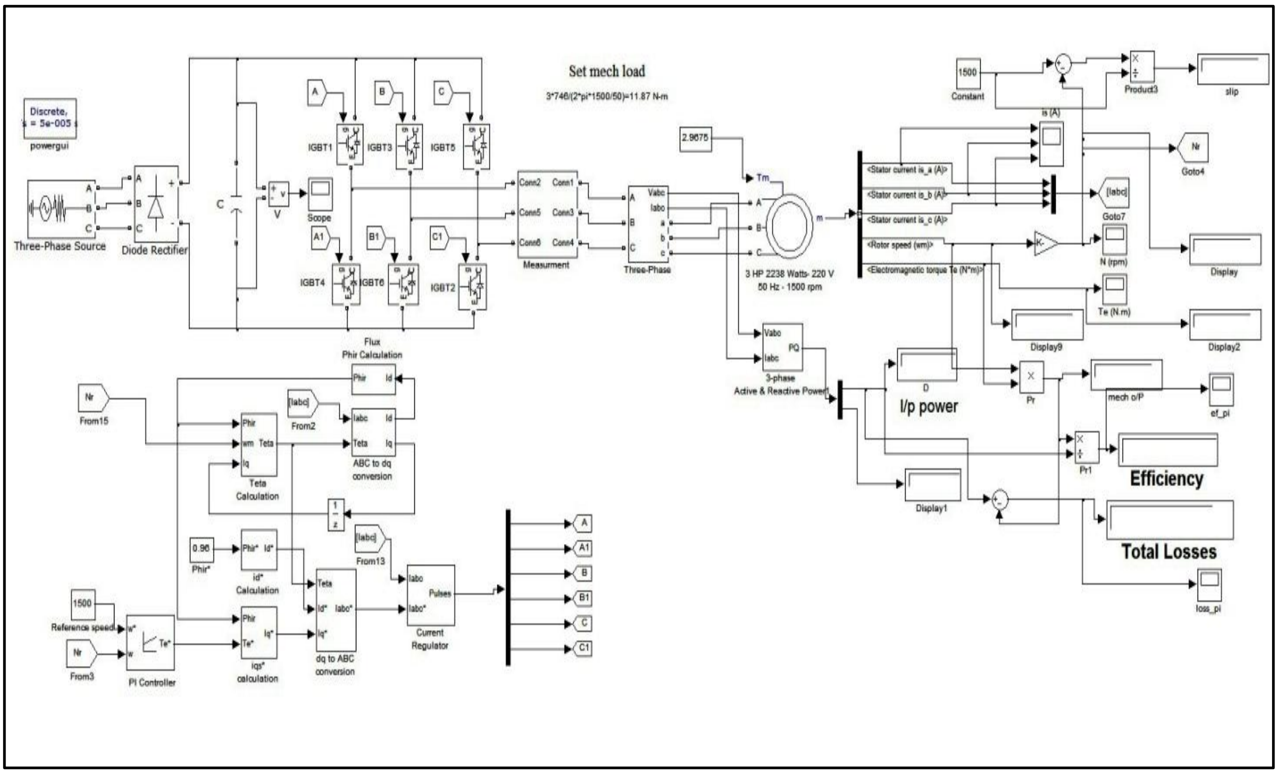

Fig. 14.Matlab Simulation model using PI controller

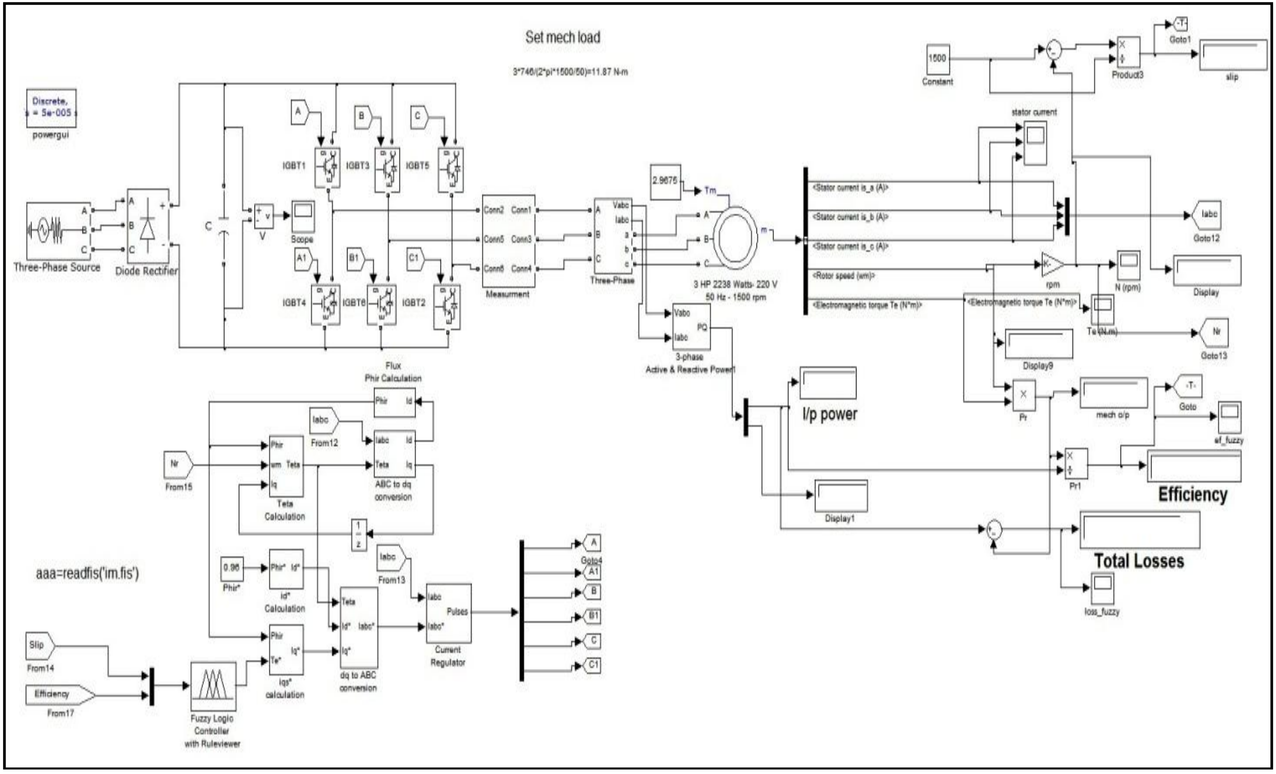

Fig. 15.Matlab Simulation model using Fuzzy logic controller

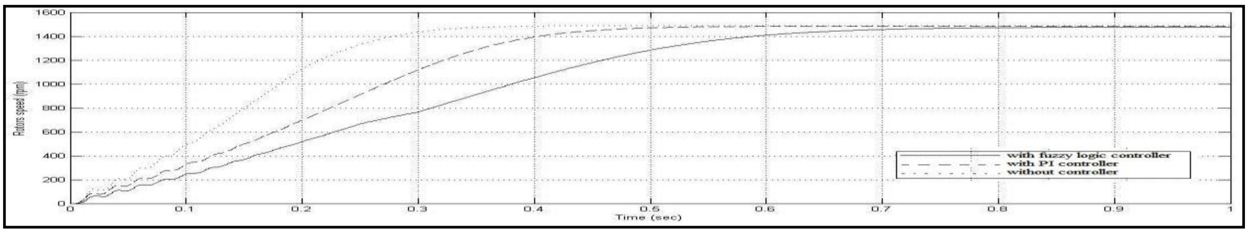

Fig. 16.Rotor speed (rpm) at T_l=2.9675 N-m

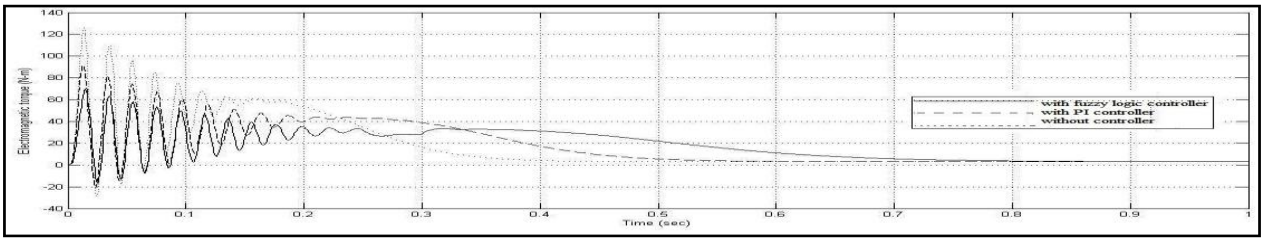

Fig. 17.Electromagnetic torque (N-m) at T_l=2.9675 N-m

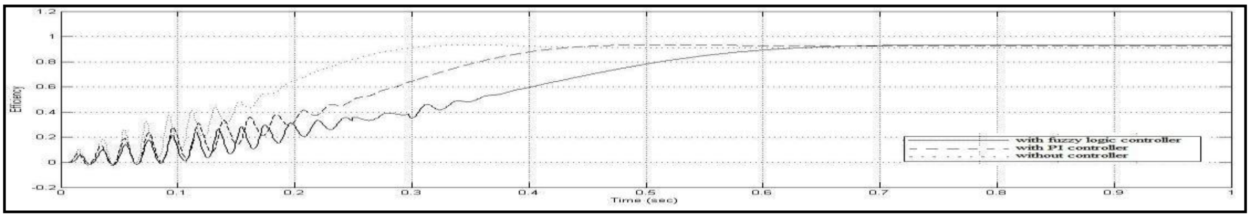

Fig. 18.Efficiency at T_l=2.9675 N-m

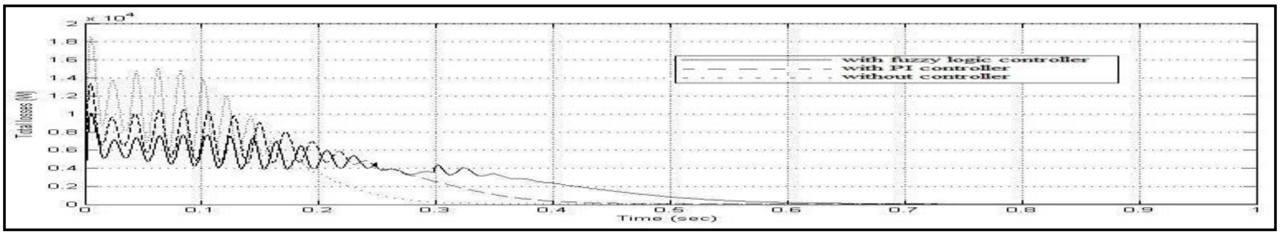

Fig. 19.Total power losses (W) at T_l=2.9675 N-m

		Table 1. Results					
Sr. No.	Mech Load (Nm)	Efficiency (Normal)	Efficiency (PI)	Efficiency (Fuzzy)	Total Losses (Normal)	Total Losses (PI)	Total Losses (Fuzzy)
1.	25%	90.95	96.21	96.37	46.36	18.18	17.34
2.	50%	93.31	95.07	96.14	66.12	47.01	36.81
3.	75%	93.24	93.19	95.22	98.99	97.95	68.43
4.	100%	92.47	91.1	94.06	146.8	171.8	113.5

VIII.CONCLUSION

The simulation results with two loss minimization techniques for indirect vector controlled voltage source inverter fed induction motor drive has been studied and compared in this paper. It is found that the output voltage obtained through inverter is reduced to low value as compared to the rms voltage of induction motor. Thus input power decreases to larger value as compared to the input power obtained without controller while change in output power is less. Hence total losses go on decreasing and efficiency goes on increasing at changing load torque. Fuzzy logic controller technique is found to be more effective over PI controller technique for efficiency optimization and loss minimization.

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APPENDIX

Specifications of Induction Motor			
Nominal Power	3 HP	Rotor Resistance	0.816 Ω
Voltage (Line to line)	220 V	Rotor Inductance	0.002 H
Frequency	50 Hz	Moment of Inertia	0.089 Kg-m^2
Stator Resistance	0.435 Ω	Number of Poles	4
Stator Inductance	0.002 H	Synchronous speed	1500 rpm

NOMENCLATURE

i_{qs}	Stator current in synchronous frame on q-axis (A)
i_{ds}	Stator current in synchronous frame on d-axis (A)
R_s	Stator resistance (Ω)
R_r	Rotor resistance (Ω)
L_r	Rotor leakage inductance (H)
L_m	Mutual inductance (H)
ω_s	Synchronous speed (rpm)
ω_r	Rotor speed (rpm)
ω_{sl}	Slip speed (rpm)
P	Number of poles of IM
T_e	Electromagnetic torque (N-m)
P_{in}	Input power (W),
P_{out}	Output power (W)