



---

## FUZZY LOGIC APPROACH OF SENSORLESS VECTOR CONTROL OF INDUCTION MOTOR USING EFFICENCY OPTIMIZATION TECHNIQUE

G. Srinivas\*

Dr. S. Tarakalyani\*\*

---

**Abstract:** *This paper deals with the fuzzy logic approach of sensor less vector control of induction motor using efficiency optimization technique. The efficiency optimization control on the basis of search, where the flux is decremented in steps until the measured input power settled down to the lowest value. The control does not require the knowledge of machine parameters, is completely insensitive to parameter changes, and is applicable universally to any arbitrary machine. a fuzzy logic based on-line efficiency optimization control is proposed for an indirect vector controlled drive system. Energy optimizing controllers interface with the ASD to minimize line power consumption and that controller is on-line efficiency optimization controller using fuzzy logic. In this analysis the performance of the drive without fuzzy controller & when it is incorporated is analyzed & compared. The above analysis is done in MATLAB /SIMULINK/ using fuzzy logic toolbox.*

**Keywords:** *vector control, fuzzy logic, speed estimator, induction motor, and efficiency optimization*

---

\*Research scholar, J.N.T.U.H. Hyderabad.

\*\*Professor, E.E.E.Dept, J.N.T.U.H. Hyderabad.



## INTRODUCTION

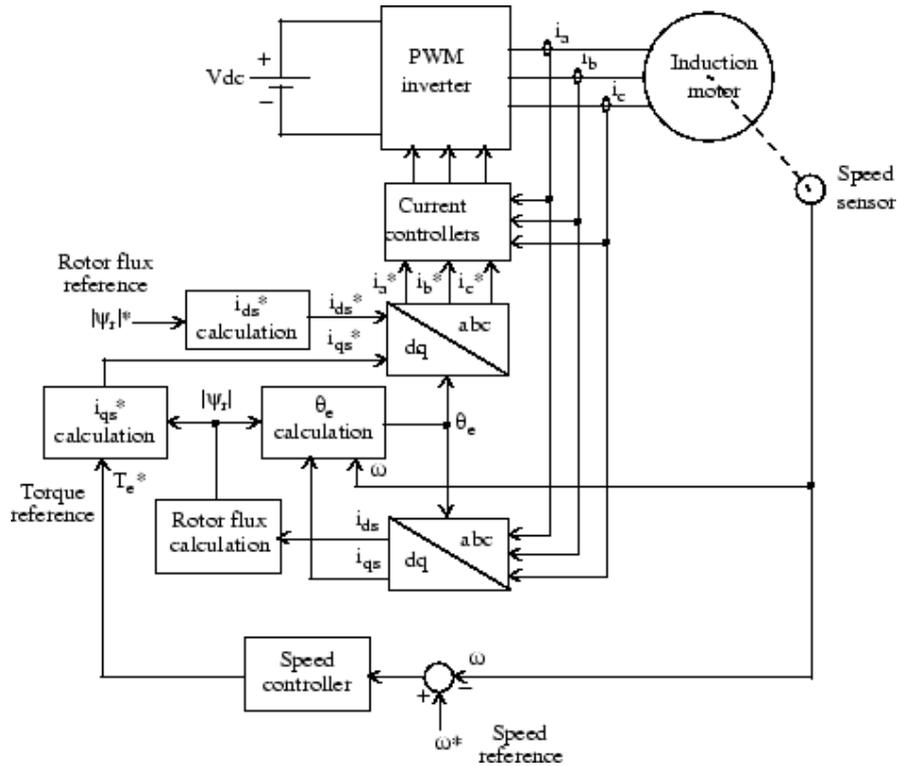
Induction motor is the work horse in industry due to its rigid construction & can work under all conditions of environment. But due to the factor that flux & torque cannot be controlled individually as the stator current is a combination of both it is not popular like D.C. Motor. But with the development of power electronics & Vector control concept the three phase stator current can be resolved into two phase components by orthogonal transformation by using Clarke's transformation & to rotor reference frame by parks transformation. To do this the position of flux vector is important. This position of flux vector can be found by direct & indirect methods where direct method employs sensors incorporated in stator which adds to cost, size & induction of harmonics. Hence in indirect control this flux vector can be found by machine parameters & modeling equations governing its performance. Hence sensor less vector control has gained importance. Basically there are various methods of indirect vector control of which Kalman filter, MRAS, sliding mode observer are in major use in earlier days, and hence these methods are prone to numerical & steady errors due to large calculations involved. Hence with the development of software's like Matlab/Simulink, & computer methods like fuzzy logic, neural networks the complications have been resolved.

The Indian power sector has come long way in power generation from 1300MW capacity during independence to 102907MW at present. However in spite of government's plans, the present power availability is not good enough to cater to the needs of the country, as there is a peak shortage of the power of around 10,000MW (13%) and 40,000 million units deficit (7.5%). Unless the system efficiency improves in terms of technical improvements, the crisis will still continue. Energy savings possible due to some major energy equipments such as transformers, motors etc.

The present paper deals with calculation of torque, speed of induction motor without optimization controller & comparing it with after installing controller using fuzzy logic approach.

$$\begin{pmatrix} V_{ds} \\ V_{ds} \\ V_{qr} \\ V_{ds} \end{pmatrix} \begin{pmatrix} (R_s + L_s P) & \omega_s L_s & L_m P & \omega_s L_m \\ -\omega_s L_s & (R_s + L_s P) & -\omega_s L_m & L_m P \\ L_m P & (\omega_{sl}) L_m & (R_r + L_r P) & \omega_{sl} L_r \\ -(\omega_{sl}) L_m & L_m P & -\omega_{sl} L_r & (R_r + L_r P) \end{pmatrix} \begin{pmatrix} I_{qs} \\ I_{ds} \\ I_{qr} \\ I_{ds} \end{pmatrix}$$

### Modeling of induction motor



#### A. Dynamic Modeling of induction motors

The dynamic model of the induction motor is derived by transforming the three-phase quantities into two phase direct and quadrature axes quantities. The equivalence between the three-phase and two-phase machine models is derived from the concept of power invariance [16]. Induction motor modeling the synchronous reference frame is shown in equation (1)

Electromagnetic Torque:

$$T_e = \frac{3}{2} \frac{P}{2} L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \quad (2)$$

The dynamic equations of the induction motor in synchronous reference frames can be represented by using flux linkages as variables. This involves the reduction of number of variables in dynamic equations, which greatly facilitates their solution. The flux-linkages representation is used in motor drives to highlight the process of the decoupling of the flux and torque channels in the induction machine. The stator and rotor flux linkages in synchronous reference frame are shown in equations (3)-(8)

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \quad (3)$$



$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \quad (4)$$

$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs} \quad (5)$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds} \quad (6)$$

$$\lambda_{qm} = L_m (i_{qs} + i_{qr}) \quad (7)$$

$$\lambda_{dm} = L_m (i_{ds} + i_{dr}) \quad (8)$$

### B. State Space model of induction motors

The space phasor model of the induction motors can be presented in state space equations from previous equation, so it can be expressed in the synchronously rotating  $d-q$  reference frame as shown in equations (9) to (17).

$$\dot{X} = AX + Bu \quad (9)$$

$$X = [i_{ds} \quad i_{qs} \quad \lambda_{dr} \quad \lambda_{qr}]^T \quad (10)$$

$$u = [V_{ds} \quad V_{qs}]^T \quad (11)$$

$$A = \begin{pmatrix} a_1 & w_e & a_2 & \frac{L_m w_r}{\sigma L_s L_r} \\ -w_e & a_1 & \frac{L_m w_r}{\sigma L_s L_r} & a_2 \\ \frac{L_m R_r}{L_r} & 0 & \frac{-R_r}{L_r} & w_e - w_r \\ 0 & \frac{L_m R_r}{L_r} & -w_e + w_r & \frac{-R_r}{L_r} \end{pmatrix} \quad (12)$$

$$B = \begin{pmatrix} a_3 & 0 \\ 0 & a_3 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \quad (13)$$

$$a_1 = \frac{-R_s}{\sigma L_s} - \frac{(1-\sigma)R_r}{\sigma L_r} \quad (14)$$

$$a_2 = \frac{L_m R_r}{\sigma L_s L_r} \quad (15)$$

$$a_3 = \frac{1}{\sigma L_s} \quad (16)$$

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \quad (17)$$

## Fuzzy efficiency Controller

### A. Efficiency Optimization Control

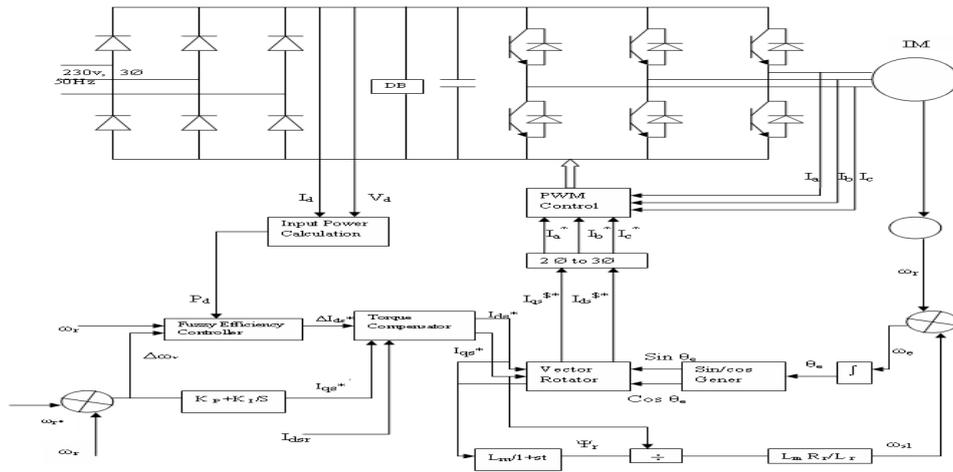


Fig. 1. shows the indirect vector controlled induction motor with efficiency optimization controller block diagram

The principle of efficiency optimization control with rotor flux programming at a steady-state torque and speed condition is explained in Fig.: 1 The rotor flux is decreased by reducing the magnetizing current, which ultimately results in a corresponding increase in the torque current (normally by action of the speed controller); such that the developed torque remains constant. As the flux is decreased, the iron loss decreases with the attendant increase of copper loss.

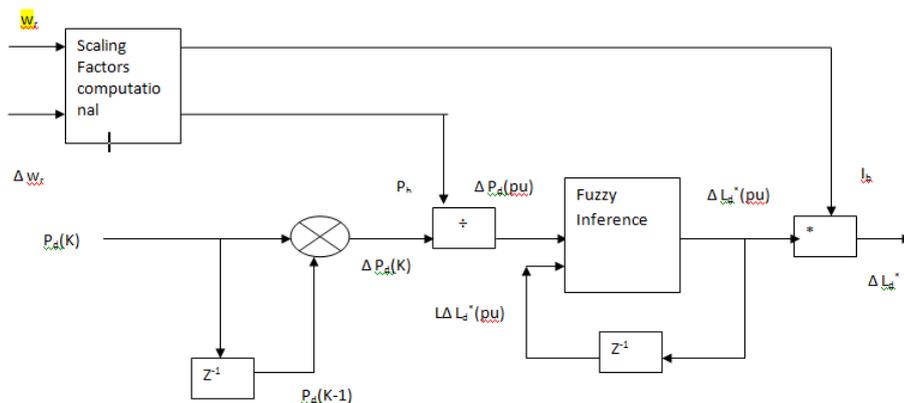


Fig.2.Efficiency optimization control block diagram



The above figure2 explains the fuzzy efficiency controller operation. The input dc power is sampled and compared with the previous value to determine the increment  $\Delta P_d$ . In addition, the last excitation current decrement ( $L \Delta i_{ds}$ ) is reviewed. On these bases, the decrement step  $\Delta i_{ds}^*$  is generated from fuzzy rules through fuzzy inference and defuzzification. The adjustable gains  $P_b$  and  $I_b$ , generated by scaling factors computation block, convert the input variable and control variable, respectively, to per unit values so that a single fuzzy rule base can be used for any torque and speed condition. The input gain  $P_b$  as a function of machine speed  $w_r$  can be given as  $P_b = a w_r + b$  Where the coefficients  $a$  and  $b$  were derived from simulation studies. The output gain  $I_b$  is computed from the machine speed and an approximate estimate of machine torque  $T_e$   $I_b = C_1 w_r - C_2 T_e + C_3$  Again, the appropriate coefficients  $c_1$ ,  $c_2$ , and  $c_3$  were derived from simulation studies. In the absence of input and output gains, the efficiency optimization controller would react equally to a specific value of  $\Delta P_b$  resulting from a past action  $\Delta i_{ds}^*(k-1)$ , irrespective of operating speed. Since the optimal efficiency is speed dependant, the control action could easily be too conservative, resulting in slow convergence, or excessive, yielding an overshoot in the search process with possible adverse impact on system stability. As both input and output gains are function of speed, this problem does not arise. The above equation also incorporates the a priori knowledge that the optimum value of  $\Delta i_{ds}^*$  is a function of torque as well as machine speed. In this way, for different speed and torque conditions, the same  $\Delta i_{ds}^*(p.u)$  will result in different  $i_{ds}^*$ , ensuring a fast convergence. One additional advantage of per unit basis operation is that the same fuzzy controller can be applied to any arbitrary machine, by simply changing the coefficients of input and output gains.

The membership functions for the fuzzy efficiency controller are shown below. Due to the use of input and output gains, the universe of discourse for all variables are normalized in the  $[-1, 1]$  interval. It was verified that, while the control variable  $\Delta i_{ds}^*$ , required seven fuzzy sets to provide good control sensitivity, the past control action  $L \Delta i_{ds}^*$  (i.e.  $\Delta i_{ds}^*(k-1)$ ) needed only two fuzzy sets, since the main information conveyed by them is the sign. The small overlap of the positive (P) and negative (N) membership functions is required to ensure proper operation of the height defuzzification method, i.e., to prevent indeterminate result in case  $L \Delta i_{ds}^*$  approaches zero. The rule base for fuzzy control is given below. The basic idea is that if the last control action indicated a decrease of dc link power, proceed



searching in the same direction and the control magnitude should be somewhat proportional to the measured dc link power change. In case the last control action resulted in an increase of Pd ( $\Delta P_d > 0$ ), the search direction is reversed, and the  $\Delta i_{ds}^*$ , step size is reduced to attenuate oscillations in the search process.

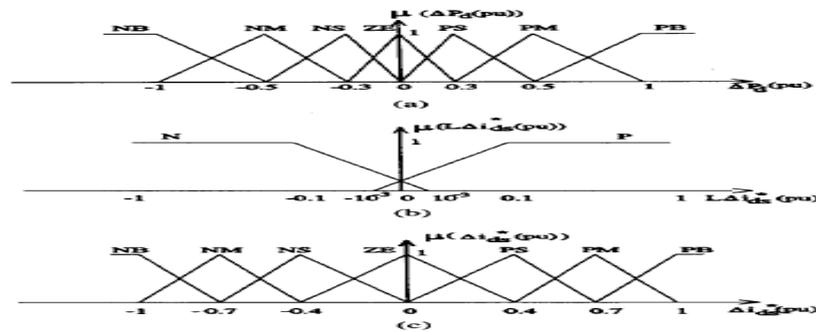


Fig.3a,b&c Membership functions for efficiency controller change of DC link power ( $\Delta P_d(\text{pu})$ ), Last change in excitation current ( $\Delta i_{ds}^*(\text{pu})$ ) & Excitation current control increment ( $\Delta i_{ds}^*(\text{pu})$ ).

Table I

$\Delta_0/\Delta_0$	N	P
PB	PM	NM
PM	PS	NS
PS	PS	NS
ZE	ZE	ZE
NS	NS	PS
NM	NM	PM
NB	NB	PB

Rules base for Fuzzy Efficiency Controller:

As the excitation current is decremented with adaptive step size by the fuzzy controller, the rotor flux  $\Psi_{dr}$  will decrease exponentially which is given by equation (18)

$$\frac{d}{dt} \Psi_{dr} = \frac{L_m i_{ds} - \Psi_{dr}}{T_r} \quad (18)$$

Where  $\lambda_r = L_r/R_r$  is the rotor time constant and  $L_m$  the magnetizing inductance. The decrease of flux causes loss of torque, which normally is compensated slowly by the speed control loop. Such pulsating torque at low frequency is very undesirable because it causes speed



ripple and may create mechanical resonance. To prevent these problems, a feed forward pulsating torque compensator has been proposed.

Under correct field orientation control, the developed torque is given by equation (19)

$$T_e = K_t i_{qs} \psi_{dr} \quad (19)$$

For an invariant torque, the torque current  $i_{qs}$ , should be controlled to vary inversely with the rotor flux. This can be accomplished by adding a compensating signal  $i_{qs}^*$  to the original  $i_{qs}^*$  to counteract the decrease in flux  $\Delta\psi_{dr}(t)$  where  $t \in [0, T]$  and  $T$  is the sampling period for efficiency optimization control. Let  $i_{qs}(0)$  and  $\psi_{dr}(0)$  be the initial values for  $i_{qs}$  and  $\psi_{dr}$ , respectively, for the  $k$ -th step change of  $i_{ds}^*$ . For a perfect compensation, the developed torque must remain constant, and the following equality given by equation (20) holds good.

$$[\psi_{dr}(0) + \Delta\psi_{dr}(t)] [i_{qs}(0) + \Delta i_{qs}(t)] = \psi_{dr}(0) i_{qs}(0) \quad (20)$$

Solving for  $\Delta i_{qs}(t)$  yields

$$i_{qs}(t) = \frac{\psi_{dr}(t) i_{qs}(0)}{\psi_{dr}(0) + \Delta\psi_{dr}(t)} \quad (21)$$

Where  $\Delta\psi_{dr}(t)$  is governed by above equation with, substituted for  $\Delta i_{ds}^*$ . To implement such compensation, above equations are adapted to produce  $i_{qs}(t)$ , using flux estimate  $\psi_{dr}$  and command in  $i_{qs}^*$  place of actual signals. A good approximate solution for  $\Delta i_{qs}(t)$  can be obtained by replacing the denominator of the above equation by its steady-state value estimate  $\Delta\psi_{dr}(t)$ . In this case the compensation can be implemented in two steps as shown in Fig. 4. First, the value for the compensating torque current step is computed by discrete  $i_{qs}^*(k)$  given by equation (22) as

$$i_{qs}^*(k) = \frac{\psi_{dr}^*(k-1) - \psi_{dr}(k)}{\psi_{dr}^*} i_{qs}(k-1) \quad (22)$$

Next, the current step is processed through a first order low pass filter of rotor time constant, and then added to the previous compensating steps. This current is added to the original speed loop generated current  $i_{qs}^*$  so that, at any instant, the product  $i_{qs} \psi_{dr}$  remains essentially constant.



## II. RESULTS

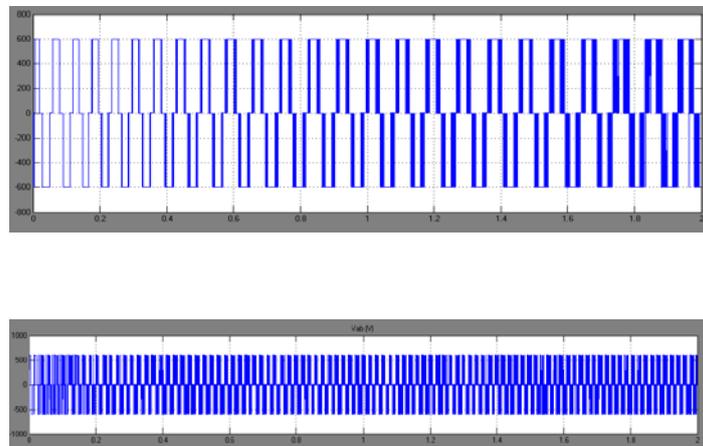
Table II

Specifications of the Induction Motor:

HP=5	Power rating of motor
V=440v	Voltage applied
F=50HZ	Frequency
N=1500RPM	Speed in RPM
P=4	No of poles
$R_s = 0.406\Omega$	Stator Resistance
$R_r = 0.478 \Omega$	Rotor Resistance
$L_{ls} = 2.13mH$	Stator Leakage Resistance
$L_{lr} = 2.13mH$	Rotor Leakage Resistance
$L_m = 49.4mH$	Mutual Inductance

The above block diagrams represent the Simulink model of the proposed methods. Figure 4 shows the model without fuzzy controller & only using PI control & Fig 5 shows the proposed fuzzy control model incorporated in vector control method. The simulation of the induction motor was done with fuzzy controller & without fuzzy controller for a simulation time of 2 seconds & the graphs for speed; voltage & torque with & without controller incorporated are as shown below.

Wave forms of voltages with PI Controller & fuzzy controller



From the simulation studies of voltage wave forms it can be concluded that the voltage is smooth & ripple free with more pulses in a given interval. Hence by using fuzzy controller the voltage is maintained at highest value with less distortion hence better performance.

### Rotor speed wave forms with PI controller & with fuzzy controller

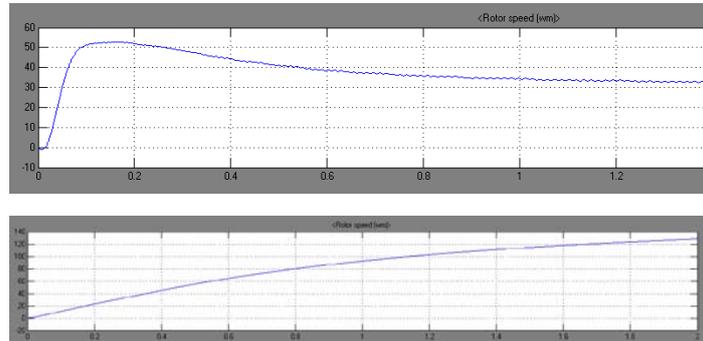


Fig. 7.

From the analysis of rotor speeds it is observed that the maximum speed that can be attained is more with controller & it is found that this speed is maintained constant. Whereas without controller the maximum speed attained is less & after a short while speed drops drastically . Hence with fuzzy controller maximum speed can be increased & maintained constant.

### Wave form for torques with PI controller & with fuzzy controller

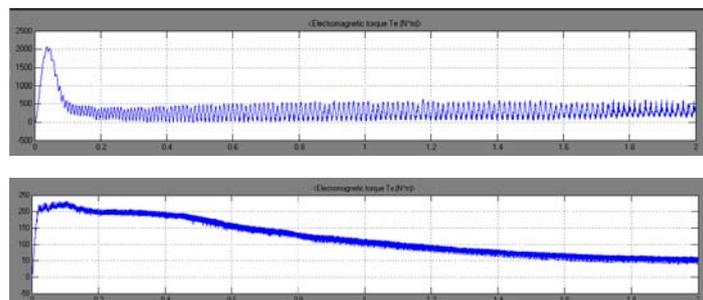


Fig. 8

The above simulation wave forms for torque show that the behavior of induction motor is as torque decreases speed increases. The torque with controller is less distorted, almost all constant without jerky operation. Hence torque is improved & almost all constant with fuzzy controller



## CONCLUSION:

This was observed mainly through the graphs obtained as outputs from the MATLAB simulink the graphs were obtained for the system with and without fuzzy controller The performance of the drive with fuzzy optimized controller is better when compared to without fuzzy controller. It is found from the graphs for voltage ,speed ,torque that voltage wave form is improved ,torque is stabilized & speed is increased with fuzzy controller . from this it is concluded that this controller gives better performance & it is superior ..It was further concluded that that for all load torques the output power is maintained almost constant. Input power minimization has been done at all load torques and the input power decreases i.e. the efficiency is increased at all loads.

## REFERENCES:

1. "Efficiency Optimization Control of A.C Induction Motors: Initial Laboratory Results ", M.W.Turner, V.E.McCornick and J.G.Cleland, *EPA Project EPA/600/SR- 96/008*
2. " Fuzzy logic based on-line efficiency Optimization of an indirect vector–controlled Induction motor drives", G.C.D. Sousa, B.K.Bose, J.G.Cleland, IEEE Transaction on Industrial Electronics, vol. 42, no.2, pp.192-198, April 1995.
3. " Fuzzy logic drives".efficiency optimization of induction based improvements in induction motor drives". Juan M. Moreno-Eguilaz, M. Cipolla-Ficarra, P.J.da Costa Branco, Juan Peracaula,
4. "A Fuzzy-Logic-Based Energy Optimizer for AC Motors" John G. Cleland ,Vance E. McCormick and M. Wayne Turner Center for Digital Systems Engineering, Research Triangle Institute, Research Triangle Park, NC 27709 Pp: 1777-1784
5. "An Efficient Controller for an Adjustable Speed Induction Motor Drive" G. O. Garcia, J. C. Mendes Luis, R. M. Stephan, and E. H. Watanabe IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 41, NO. 5, OCTOBER 1994 533 Pp: 533-539
6. "Loss Minimization Control of an Induction Motor Drive" Parviz amouri and Jimmie J. Cathey, Senior Member, IEEE IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 27. NO. 1, JANUARY IFEBRUAR 1991 Pp: 32-37
7. "An Efficiency-Optimization Controller for Induction Motor Drives" M.E.H. Benbouzid, N.S. Nait Said Pp: 63-64
8. "Fuzzy Efficient-Optimization Controller for Induction Motor Drives" F. Zidani, M.E.H. Benbouzid, D. Diallo Author Affiliation: University of Picardie "Jules Verne," 7, Rue du Moulin Neuf, 80000 Amiens, France. pp:43-44



9. "Loss Minimization of a Fuzzy Controlled Induction Motor Drive" F. Zidani\*, M.E.H. Benbouzid, Senior Member, IEEE and D. Diallo, Member, IEEE University of Batna, Algeria Centre de Robotique, d'Electrotechnique et d' Automatique University of Picardie "Jules Verne"7, Rue du Moulin Neuf - 80000 Amiens, France Pp: 629-633
10. "Fast Efficiency Optimization Techniques for the Indirect Vector-controlled Induction Motor Drives" Chandan Chakraborty, Senior Member, IEEE, and Yoichi Hori, Senior .