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Comparative Study of PI, PID and Fuzzy PI Controller Based Direct Torque Control Induction Motor Drive

Amandeep Jakhar[1] and Prerna Gaur[2]

[1,2]Dept. of Instrumentation and Control Netaji Subhash Institute Of Technology New Delhi ,India
E-mail: [1]jakharamandeep09@gmail.com, [2]prernagaur@yahoo.com

Abstract—*This paper presents a method for refining the speed contour of induction motor drive in Direct Torque Control (DTC) using proposed fuzzy-PI based speed controller. Due to multi-variable, strong coupling, nonlinear and time-varying characteristics of Induction Motor Drive (IMD), it is difficult for traditional PI, Proportional Integral Drive (PID) controller with DTC system to get ideal performance. To enhance the performance of DTC system, traditional PI is first replaced by PID and then by fuzzy-PI controller. According to the principal of DTC, a model of DTC Induction Motor Drive (IMD) with fuzzy-PI based speed controller is formulated and simulation is implemented. In comparison with the traditional PID regulator, the simulation shows that the fuzzy-PI based speed controller is more efficacious in refining the speed response and stability of DTC system.*

1. INTRODUCTION

The electric drives are used in control of motion. Today, around 70% of electric power is consumed by electric drives. The electric drives are of two types AC and DC drives. From last four decades AC drives are used more in industries, Especially Induction Motor Drives (IMD) because of advantages like simple construction, ruggedness, reliability, low cost, and low maintenance. However, due to their highly coupled nonlinear structure, control of Induction Motor Drive (IMD) is a challenging problem [1].

Induction Motor Drive (IMD) control strategies are of two type: scalar and vector control. The general classification of the variable frequency controls is presented in Fig.1.The scalar control operates in steady state not in space vector position during transient state. The vector control operates in both states. In the vector control, widely used methods are Field Oriented Control (FOC) presented by F.Blaschke (Direct FOC) and Hasse (Indirect FOC) in early 1970's[2], and Direct Torque Control (DTC) presented by Isao Takahashi and Toshiko Noguchi, in mid 1980's [3].

In the FOC, the motor equations are transformed into a coordinate system that rotates in synchronism with the rotor flux vector control [2]. This drawback was removed by using DTC which is based on maintain the amplitude of stator flux constant, avoiding electromagnetic transients, and disadvantages like possible problems during starting, torque and flux ripples.

The most widely used controller in the industrial application are PI and PID-type controller because of simple structure and good performance in wide range operating conditions [4]. The main problem of that simple controller is the correct choice of the PID gains, and by using fixed gains, the controller may not provide the required performance, which variations in parameters and operating conditions of plant occur.

In this paper fuzzy-PI based controller is introduced to remove the disadvantages of the PID controller mention above, gain value of PI controller are tunned on-line. This controller provide the following advantages: dynamically adjust the gain Kp and Ki to ensure stability, soft speed response, reducing the speed overshoot, extremely small steady state error.

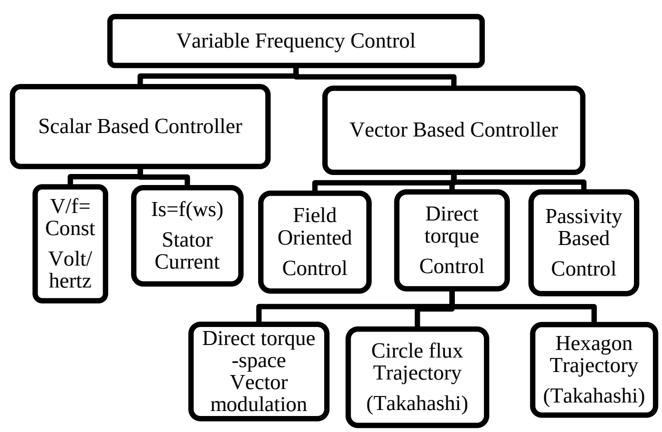


Fig. 1: Classification of Induction motor control method.

2. VECTOR MODEL OF INVERTER OUTPUT VOLTAGE

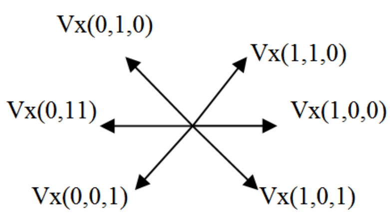
For three-phase Voltage Source Inverter (VSI) with three leg, there are 8-possible stator voltage vectors, to control the torque and flux to follow the reference values within hysteresis bands. The voltage space vector of a three phase system can be written as

$$V_x(t)=2/3\,(v_{xa}(t)+zv_{xb}(t)+z^2v_{xc}(t)) \quad ...(1)$$

$$\text{Where } z=e^{j2/3\pi} \quad ...(2)$$

v_{xa}, $v_{xb,}$, v_{xc} are the instantaneous phase voltages.

From equation (1) above there are 6-non zero states and 2-null states as shown if figure(2) below



When using a DC-link voltage of v_d, the voltage space vector by using equation (1) is given by

$$V_x(t)=2/3\,v_d\,(s_a(t)+zs_b(t)+z^2s_c(t)) \quad ...(3)$$

3. MATHEMATICAL MODEL OF INDUCTION MOTOR DRIVE

The mathematical model of induction motor drives when the motor operates in both the steady state and transient states. The standard IMD equivalent model can be used to calculate motor variables such as developed torque, flux, stator voltage, stator current, and rotor current etc. The induction motor can be modeled with stator current and flux in reference ($i_{ds}-i_{qs}$) as state variable expressed as follows.

$$p(t)=Ap(t)+Bj(t) \quad ...(4)$$

$$g(t)=Cp(t) \quad ...(5)$$

Where A is system matrix, B is the control and C is the observation, and p(t) is the state variable, j(t) is input vector and g(t) is output vector. An improved method of speed estimation that operates on the principal of a speed adaptive flux observer. An observer is basically an estimator that uses a plant model and a feedback loop with measured plant variables. The machine model in $i_{ds}-i_{qs}$ frame, where the state flux variables are ϕ_{ds}^s and ϕ_{ds}^s, and stator currents i_{ds} and i_{qs} [5].

$$g(t)=[i_{ds}\ i_{ds}]^T$$

$$p(t)=[i_{ds}^s\ i_{qs}^s\ \phi_{ds}^s\ \phi_{ds}^s]^T$$

$$j(t)=[U_{ds}^s\ U_{qs}^s\ 0\ 0]^T$$

$$A=\begin{bmatrix}-\alpha & 0 & \frac{\beta}{\tau_m} & \beta\omega_m \\ 0 & -\alpha & -\beta\omega_m & \frac{\beta}{\omega_m} \\ \frac{L_m}{\tau_m} & 0 & \frac{-1}{\tau_m} & \omega_r \\ 0 & \frac{L_m}{\tau_r} & \omega_r & \frac{-1}{\tau_r}\end{bmatrix}$$

$$B=\begin{bmatrix}\frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0\end{bmatrix}$$

$$C=\begin{bmatrix}1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0\end{bmatrix}^T$$

$$\text{Where } \alpha=\left[\frac{R_s}{\sigma L_s}+\frac{L_m^2}{\sigma L_s L_r \tau_r}\right]$$

$$\beta=\frac{L_m}{\sigma L_s L_r}$$

$$\tau_r=\frac{L_r}{R_r},\ \tau_s=\frac{L_s}{R_s},\ \sigma=1-\frac{L_m^2}{L_s L_r}$$

4. DIRECT TORQUE CONTROL

This method was presented in the middle of 1980's by Isao Takahashi and Toshihiko Noguchi [6]. The principles of Direct Torque Control method, choose one of the inverters 6 voltage vectors and two zero vectors in order to keep the stator flux and torque into a hysteresis band around the required flux and torque magnitudes[6].

$$T=\frac{1}{L_m}\frac{3}{2}p|\phi_s||\phi_r|sin\theta \quad ...(6)$$

Where ϕ_s is stator flux, ϕ_r is rotor flux (both based on stationay frame) and θ is angle between stator flux and rotor flux, p is the number of poles. According to the above equation(6) which shows the torque produced is dependent on stator flux magnitude, rotor flux magnitude, and phase angle between the stator and rotor flux vectors.

$$\Delta\phi_s = V_x.\Delta t \quad \dots (7)$$

Over a short period this means that the change in stator flux vector is determined by the applied voltage vector as shown in figure (2).If the flux and torque are into their hysteresis bands as shown in figure (3) by choosing exact voltage vectors an independent control over the torque and stator flux is achieved.

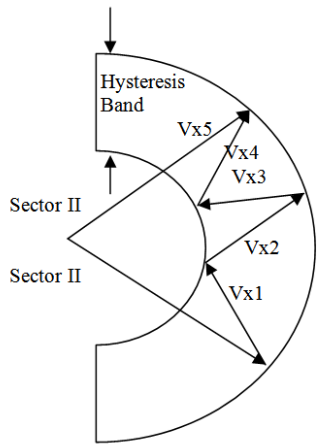


Fig. 3: .Flux control within Hysteresis band.

A table of 36 state can be made for stator flux and torque either increase or decrease.

Table 1: The switching table for the DTC

	SECTOR	1	2	3	4	5	6
FLUX	**TORQUE**						
Δφ=1	ΔT=1	V_2	V_3	V_4	V_5	V_6	V_1
	ΔT=0	V_7	V_0	V_7	V_0	V_7	V_0
	ΔT=-1	V_6	V_1	V_2	V_3	V_4	V_5
Δφ=0	ΔT=1	V_3	V_4	V_5	V_6	V_1	V_2
	ΔT=0	V_0	V_7	V_0	V_7	V_0	V_7
	ΔT=-1	V_5	V_6	V_1	V_2	V_3	V_4

5. FUZZY LOGIC CONTROLLER

The fuzzy logic controller is from artificial intelligent family. In this paper the Mamdani type fuzzy logic controller is used. For DTC of induction motor drive using PID controller based speed regulator requires precise mathematical model of the plant and appropriate gain values of PID controller for good performance. Therefore, uneven change in load conditions would produce overshoot, oscillation, long settling time, high torque ripples, and high stator flux ripples. For the removal of this problem, a fuzzy control rule look-up table is designed from the performance of speed response of DTC in induction motor drive. On the basis of speed error and change in speed error, the gain values for PI are adjusted on-line .

A FLC converts a linguistic control strategy to automatic control strategy, and fuzzy rules are designed on expert knowledge and database. At first, the reference speed and change in error speed been placed to the input variables of the FLC and the output we get is gain values for the PI controller.

6. STRUCTURE OF FUZZY PI CONTROL SYSTEM

The figure below shows the fuzzy based PI controller for direct torque control (DTC).

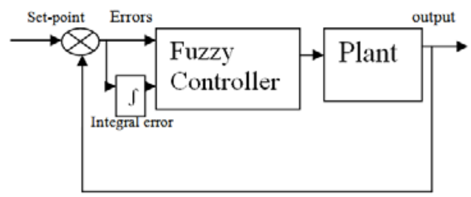


Fig. 4: Block diagram of Fuzzy PI Control System.

As shown above in this method scaled values of speed error and change in speed error are used for the fuzzy controller to give the proportional gain and integral gain.

7. FUZZIFICATION

The range of fuzzy controller inputs :error and change in error are characterized into seven and three overlapping fuzzy subsets respectively on the other hand output: proportional gain and integral gain, into four overlapping fuzzy subsets and triangular membership functions are used. The symbols used in memberships are given in the tables.

Table 2: Linguistic term for error

Linguistic Term	Symbol
Negative Large	NL
Negative Medium	NM
Negative Small	NS
Zero Error	ZE
Positive Small	PS
Positive Medium	PM
Positive Large	PL

Table 3: Linguistic term for change-of-error

Linguistic Term	Symbol
Negative	N
Zero	Z
Positive	P

Table 4: Linguistic Term for proportional gain and integral gain

Linguistic Term	Symbol
Zero	Z
Small	S
Medium	M
Large	L

Table 5: Fuzzy Control Linguistic Roles for Proportional Gain

de(t) \ e(t)	NL	NM	NS	ZE	PS	PM	PL
N	L	M	S	M	S	M	L
Z	L	M	L	Z	L	M	L
P	L	M	L	Z	L	M	L

Table 6: Fuzzy Control Linguistic Roles for Integral Gain

de(t) \ e(t)	NL	NM	NS	ZE	PS	PM	PL
N	Z	S	M	L	M	S	Z
Z	Z	S	M	L	M	S	Z
P	Z	M	L	L	L	M	Z

8. DEFUZZIFICATION

The rules in the FLC gives desired output variable in a linguistic variable, according to the real world requirements linguistic variables could transformed to crisp output. But in this to get defuzzification output value can be acquired by using linear transform to the output value. The linear transform formula of proportional coefficient Kp and integral coefficient Ki is listed as follows:

$$Kp=40+0.8(Kpo-25)$$

$$Ki=1300+0.003(Kio-2.5)$$

Where Kpo ,Kio are defuzzification value of Kp and Ki respectively.

9. SIMULATION RESULTS

To examine the simulation result of Direct Torque Controlled (DTC) Induction Motor Drive (IMD) and the parameter values as shown in Table(7)

Table 7: Rated data of the simulated induction motor

Rated Voltage	460V
Maximum Torque	1500 N.m
Poles	4
Rated Speed	1720 RPM
Stator Resistance	14.85mOHM
Rotor Resistance	9.295mOHM
Stator Leakage Inductance	0.3027mH
Rotor Leakage Inductance	0.3027mH
Mutual Inductance	10.46mH
Moment of Inertia	3.2

Figure(5) shows the speed response for the speed response for the direct torque control using conventional PI controller, and the operating conditions are at t=0 s, the speed set point is 500 rpm, and at t=1 speed set point is 0 rpm, and the torque passing from 0 to 792 N.m. Figure(6) shows the developed electromagnetic torque of this motor at the operating condition.

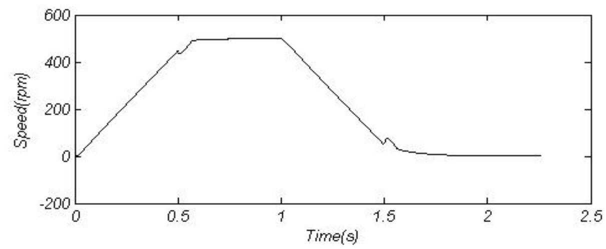


Fig. 5: Speed response for PI controller

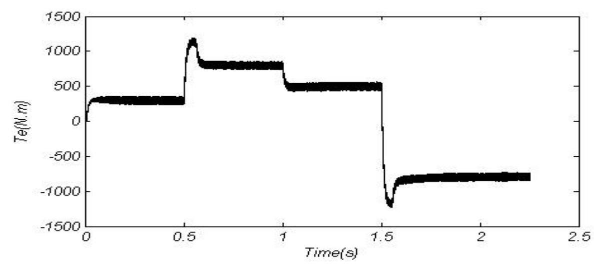


Fig. 6: Electromagnetic Torque response for PI controller

And now Fig. 7) and Fig. 8) shows the speed and electromagnetic response for PID controller for same operating conditions.

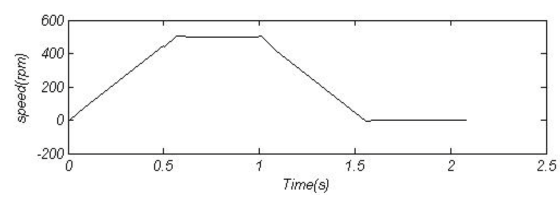


Fig. 7: Speed response of PID controller

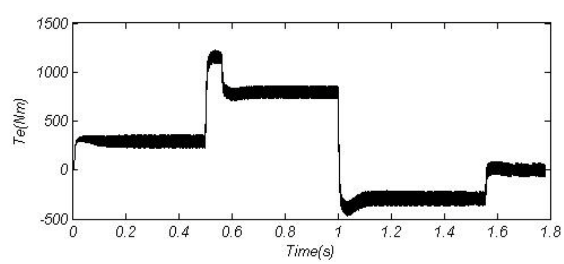


Fig. 8: Electromagnetic Torque response of PID controller

And Fig. 9) and Fig. 10) shows the speed and electromagnetic torque response of fuzzy-PI controller.

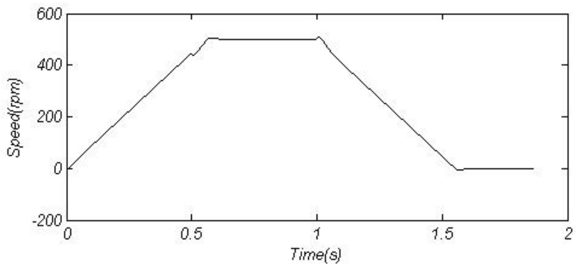


Fig. 9: Speed response of Fuzzy-PI controller

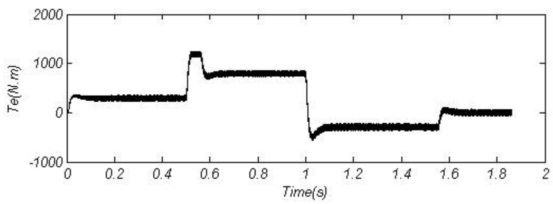


Fig. 10: Electromagnetic Torque of Fuzzy-PI controller

10. CONCLUSION

This paper present a comparative study for PI, PID and fuzzy-PI controller to overcome the disadvantages of classical PI direct torque control. This study has successfully demonstrated the design and implementation of adaptive fuzzy-pi based controller by neglecting overshot in the speed response and minimizing the rise time compared with the same results obtained from PI and PID controller.

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