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Comparison of PI and Adaptive Fuzzy PID Controllers for Speed Control of BLDC Motor

Lakshmi Mohan

Mtech Scholar, Power Electronics, TocH Institute of Science & Technology, Ernakulam, Kerala, India

Abstract: Brushless DC (BLDC) motors are commonly used in applications that require high reliability, high efficiency and high power-to-volume ratio such as industrial automations, manufacturing, robotics and aerospace. The speed of a brushless dc motor can be controlled in a closed loop by measuring the actual speed of the motor.PI (Proportional Integral), PID (Proportional Integral Derivative) and fuzzy controllers are commonly used for the speed control. This paper compares the speed responses of a brushless dc motor obtained with the adaptive fuzzy PID controller and conventional PI controller. The adaptive fuzzy PID controller proposed in the system is a parallel combination of two controllers- fuzzy PD controller and a fuzzy PI controller. Switching action take place between the two controllers based on the speed error signal received. MATLAB/Simulink is used for the simulation. Various control system parameters such as steady state error, rise time, peak overshoot, recovery time and settling time for both the controllers are analysed and compared.

Keywords: Brushless DC Motor (BLDC), PI Controller, Adaptive fuzzy, speed control, PWM inverter.

I. INTRODUCTION

Permanent magnet synchronous motors are also known as permanent magnet ac (PMAC) motors. They are classified based on the nature of voltage induced in the stator as sinusoidal PMAC and trapezoidal PMAC [1]. In the former the induced voltage has sinusoidal shape whereas the induced voltage has trapezoidal shape in the later. The self controlled variable frequency drives employing a trapezoidal PMAC motor are called brushless dc motor drives or trapezoidal PMAC motor drives [2].A brushless dc machine is basically a synchronous machine with a permanent magnet in the rotor circuit. The armature windings, which are mounted on the stator, are electronically switched according to the rotor position. Most of the adjustable speed drives require precise and continuous control of speed with long-term stability, good transient performance and high efficiency.

The dc motor satisfies some of these requirements, but the presence of commutator and brushes makes it less flexibile.BLDC motor has the following advantages over induction motor[3]- high torque to inertia ratio; high efficiency; better speed versus torque characteristics; compact size, less maintenance. Many varieties of control techniques such as PI, PID, fuzzy logic controller [4] and adaptive fuzzy controllers [5] have been introduced for the speed control of the BLDC motor. The adaptive controllers are found to be more efficient in tracking the speed under conditions of external disturbances[6].Anti wind up PID control technique is used for variable speed drives[7]Variable structure theory based tracking controller can also be incorporated [8], with which the rotor position traces an arbitrarily chosen track with high accuracy.

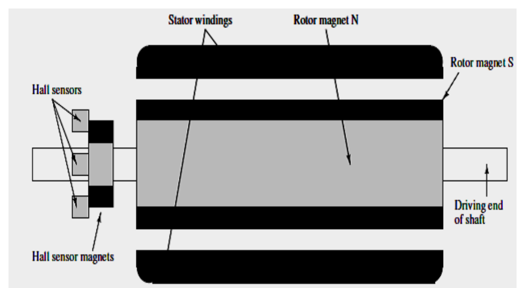

Fig.1 BLDC motor transverse section [1]

II. MODELLING OF BLDC MOTOR

The model of BLDC motor is developed considering the following assumptions:

1. The stator windings are star connected.
2. The supply system is balanced.
3. No power losses in the inverter.
4. The air gap is uniform.
5. The inverter employs a 180 degree six step switching.

The equivalent circuit of a BLDC motor is given in Figure2.

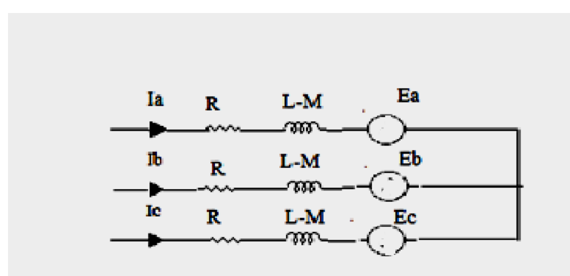

Fig2 Equivalent circuit of a BLDC motor

The voltage across the motor winding is expressed as

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$$V_a=R_a i_a+L_a \frac{di_a}{dt}+M_{ab}\frac{di_b}{dt}+M_{ac}\frac{di_c}{dt}+E_a$$

$$V_b=R_b i_b+L_b \frac{di_b}{dt}+M_{ba}\frac{di_a}{dt}+M_{bc}\frac{di_c}{dt}+E_b$$

$$V_c=R_c i_c+L_c \frac{di_c}{dt}+M_{ca}\frac{di_a}{dt}+M_{cb}\frac{di_b}{dt}+E_c$$

V_a, V_b, V_c denotes the motor phase voltage, R_a, R_b, R_c represent stator winding resistances, i_a, i_b, i_c are motor phase currents. Self inductance of the motor winding is denoted by L_a, L_b, L_c and mutual inductances between stator windings are represented as $M_{ab}, M_{ac}, M_{ba}, M_{bc}, M_{ca}, M_{cb}$.The backemf waveforms E_a, E_b, E_c are functions of angular velocity of the rotor shaft.$E=K_e*\omega_m$, where K_e is the back emf constant.The mathematical model of BLDC motor can be represented in matrix form with the following considerations:$L_a=L_b=L_c=L$, since stator self inductances are independent of rotor positions. Also,$M_{ab}= M_{ac}= M_{ba}= M_{bc}= M_{ca}= M_{cb}= M$ and $R_a=R_b=R_c=R$, since for a balanced system all the phase resistances are equal. Thus the voltage equation can be expressed in the form of a matrix as shown

$$\begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix}$$

The electromechanical torque is expressed as

$$T_{em}=J\frac{dw_m}{dt}+Bw_m+T_L$$

where J is the moment of inertia is the frictional coefficient and w_m is the angular velocity of the motor and T_L is the load torque.

$$T_{em}=\frac{1}{w_m}(E_a i_a+E_b i_b+E_c i_c)$$

The trapezoidal back emf waveforms are modelled as a function of rotor position as

$$\begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} = K_e w_m \begin{bmatrix} f_a(\theta) \\ f_b(\theta) \\ f_c(\theta) \end{bmatrix}$$

where $f_a(\theta), f_b(\theta), f_c(\theta)$ are functions of rotor position.

$$f_a(\theta)=\begin{cases} (6/\pi)\theta & \left(0\angle\theta\le \pi/6\right) \\ 1 & (\pi/6\angle\theta\le 5\pi/6) \\ -(6/\pi)\theta+6 & (5\pi/6\angle\theta\le 7\pi/6) \\ -1 & (7\pi/6\angle\theta\le 11\pi/6) \\ (6/\pi)\theta+12 & (11\pi/6\angle\theta\le 2\pi) \end{cases}$$

$f_b(\theta)$ and $f_c(\theta)$ are 120 degree and 240 degree phase shifted with respect to $f_a(\theta)$.

III.BLDC MOTOR SPEED CONTROL

The speed control loop of a brushless dc motor adjusts the applied voltage in order to reach the reference speed. The difference between the actual speed and reference speed determines the error. By increasing or decreasing the duty cycle of the inverter switches, the applied voltage can be changed so as to minimize the error. Two control loops are used to control BLDC motor. The inner current control loop (usually a hysteresis current controller) synchronizes the inverter gate signals with the emf.The outer speed control loop compares the speed of the motor with its reference value and the speed error is processed. The output of this controller is considered as the reference torque. PI, PID, fuzzy controllers are generally used in the speed control loop.

IV SYSTEM DESCRIPTION

The proposed system ,as shown in fig 3,consists of BLDC motor, three phase voltage source inverter, speed controller, commutation logic and position sensor. BLDC motor is fed by a three phase MOSFET/IGBT based inverter. The PWM gating signals for firing the power semiconductor devices in the inverter is generated by the commutation logic block. The hall sensors are used as the position sensors. They detect the rotor position. Whenever rotor magnetic poles (N or S) pass near the hall sensor, they generate a high (1) or low (0) level signal, which can be used to detect the position of shaft. The commutation logic block generates emf based on the hall signals. The gating pulses are then generated based on the emf. Generation of emf based on hall signal as well as gate signal generation based on emf are as depicted in tables I&II. The actual speed is sensed and the speed controller block process the error signal (difference between the reference and actual speed).Adaptive fuzzy PID controller is used as the speed controller in the proposed system. For comparison purpose, a PI controller is also incorporated. The proposed controller is a parallel combination of two controllers-fuzzy PI controller and fuzzy PD controller. Speed error and change in speed error are given as inputs to the two controllers. Switching takes place between these controllers based on the error signal.

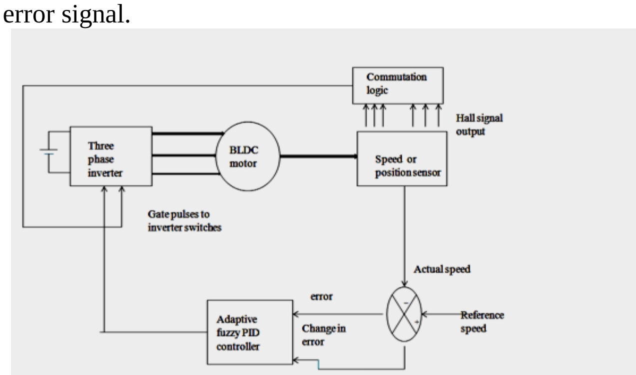

Fig 3. Block diagram of the proposed system

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The fuzzy PI controller improves the steady state response of the system and minimizes the steady state error. The fuzzy PD controller improves the transient response of the system and minimizes the rise time. The two controllers are differentiated on the basis of the fuzzy rules assigned to them. The fuzzy variable error and change in error has seven sets: positive big (PB), positive medium (PM), positive small (PS), zeros (ZE), and negative small (NS), negative medium (NM) and negative big (NB), with each set having its own membership function. Triangular membership functions are usually used. Mamdani type of fuzzy controller with 49 rules is designed.

Table I EMF generation based on hall signal

H_A	H_B	H_C	E_A	E_B	E_C
0	0	0	0	0	0
0	0	1	0	-1	1
0	1	0	-1	1	0
0	1	1	-1	0	1
1	0	0	1	0	-1
1	0	1	1	-1	0
1	1	0	0	1	-1
1	1	1	0	0	0

Table II Gate signal generation from EMF

E_A	E_B	E_C	Q1	Q2	Q3	Q4	Q5	Q6
0	0	0	0	0	0	0	0	0
0	-1	1	0	0	0	1	1	0
-1	1	0	0	1	1	0	0	0
-1	0	1	0	1	0	0	1	0
1	0	-1	1	0	0	0	0	1
1	-1	0	1	0	0	1	0	0
0	1	-1	0	0	1	0	0	1
0	0	0	0	0	0	0	0	0

Table III Rules for fuzzy PI controller

e/ce	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PB	PB	PB	NM	ZE	ZE
NM	PB	PB	PB	PM	PS	ZE	ZE
NS	PB	PM	PS	PS	PS	ZE	ZE
ZE	PB	PM	PS	ZE	NS	NM	NB
PS	ZE	ZE	NM	NS	NS	NM	NB
PM	ZE	ZE	NS	NM	NB	NB	NB
PB	ZE	ZE	NM	NB	NB	NB	NB

Table IV Rules for fuzzy PD controller

e/ce	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PB	PB	PB	PM	PS	ZE
NM	PB	PB	PB	PM	PS	ZE	NS
NS	PB	PB	PM	PS	ZE	NS	NM
ZE	PB	PM	PS	ZE	NS	NM	NB
PS	PM	PS	ZE	NS	NM	NB	NB
PM	PS	ZE	NS	NM	NB	NB	NB
PB	ZE	NS	NM	NB	NB	NB	NB

V. SIMULATION RESULTS

The simulation of the entire system is obtained using MATLAB/SIMULINK.The simulation is performed with a BLDC motor of 1.3HP, 500V dc, 3000rpm rated speed. The simulation results obtained with the PI controller and adaptive fuzzy PID controllers are compared.

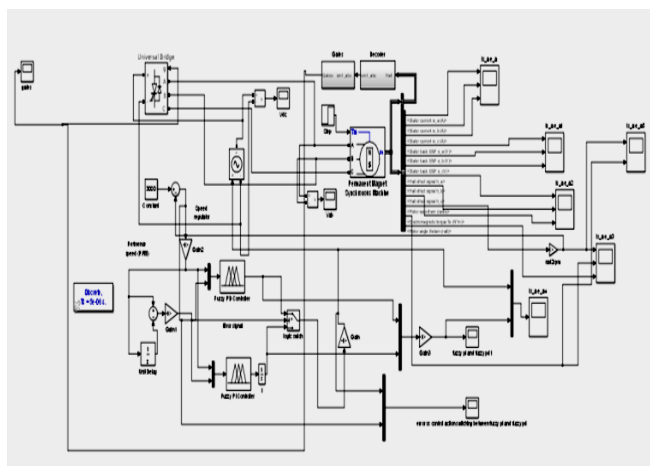

Fig 4. Simulink diagram of the proposed adaptive fuzzy PID controller

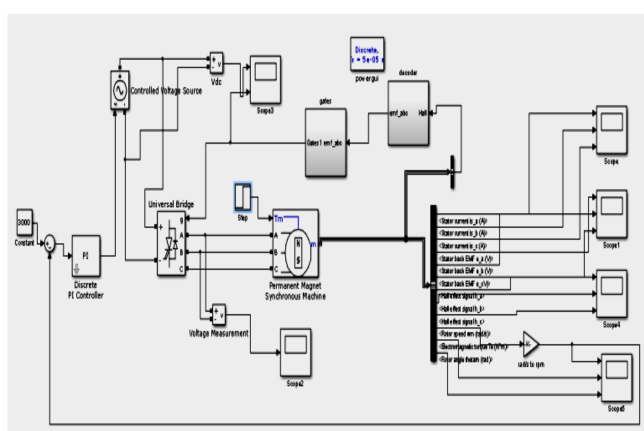

Fig 5. Simulink model of the system using PI controller

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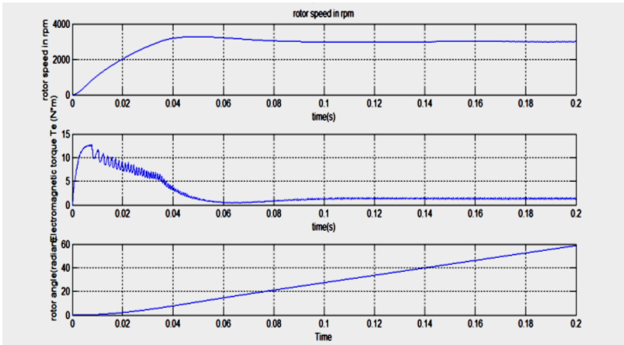

Fig6 (a) speed and torque response (ref speed=3000rpm, load torque=1Nm) obtained with PI controller

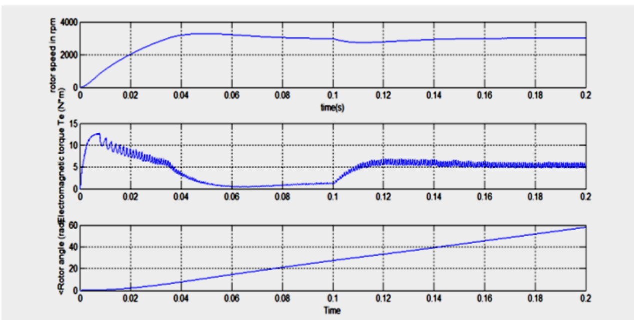

Fig6 (b) Speed and torque responses with PI controller for change in load torque (from 1Nm to 5Nm at t=0.1s, ref speed=3000rpm)

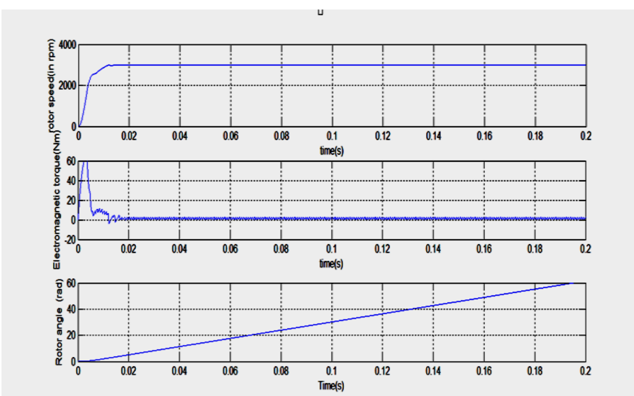

Fig7 (a) Speed and torque response obtained with proposed adaptive fuzzyPIDcontroller (refspeed3000rpm, load torque=1Nm)

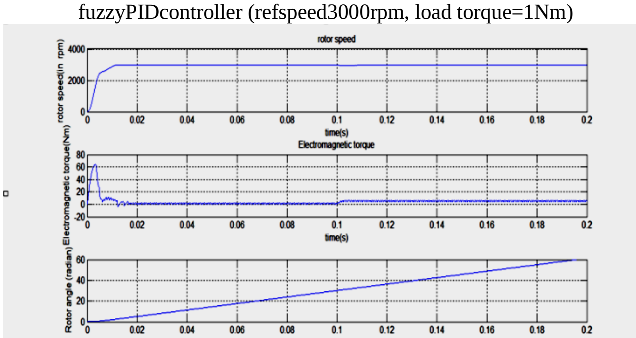

Fig7 (b) Speed and torque response with adaptive fuzzy PID controller for change in load torque from (1Nm to 5Nm at t=0.1 s, ref speed=3000rpm)

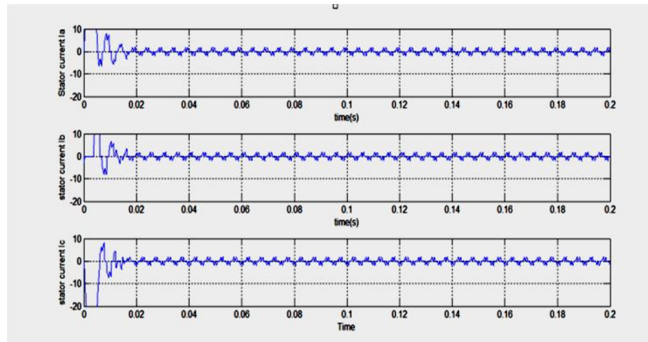

Fig 7(c) stator current waveforms obtained with the proposed controller

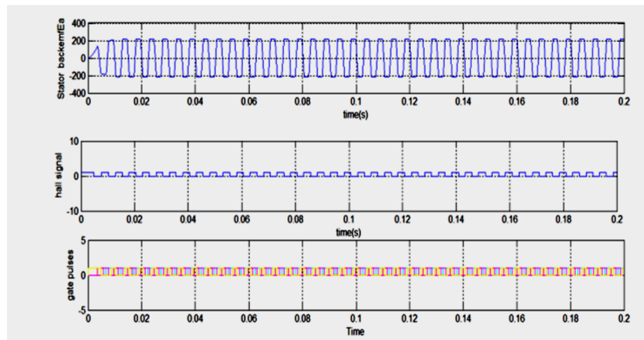

Fig7 (d) backemf, hall signal and gate pulses waveforms with the proposed controller

Based on the simulation results, the performance of the two controllers are analysed and the results are summarized in the table as follows:

Table V Comparison of PI and adaptive fuzzy PID controllers

Load conditions	PI controller	Adaptive fuzzy PID controller
Constant load torque(1Nm)	Overshoot=9.3% Settling time=0.08s Steady state error=0	Overshoot=0 Settling time=0.016s Steady state error=0
Change in load torque(from 1Nm to 5Nm in 0.1s)	Overshoot=9.33% Undershoot=8.67% Recovery time=0.15s Steady state error=0 Settling time=0.08s	Overshoot=0 Undershoot=1.66% Recovery time=0.02s Steady state error=0 Settling time=0.012s

VI **CONCLUSION**

The performance of three phase BLDC motor with adaptive fuzzy PID and PI speed controllers are analysed. Adaptive fuzzy PID controller is the parallel combination of fuzzy PD and fuzzy PI controller and has the combined advantages of both. The performance of the two controllers are compared on the basis of various control system parameters such as steady state error, rise time, peak overshoot, recovery time and settling time. It is found that the control concept with adaptive fuzzy logic PID controller outperforms classical PI controller in most of the aspects. Simulation results of the two controllers have been presented. As a future scope the adaptive fuzzy controller used in this system can be upgraded to an adaptive neuro fuzzy controller that has the combined advantages of both the neural networks and fuzzy logic

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BIOGRAPHY

Lakshmi Mohan obtained her bachelor's degree from Mahatma Gandhi University, Kerala. She is currently pursuing her Masters degree in Power electronics from Cochin University of science and technology, Kerala. Her area of interest includes power electronics, electrical drives and control systems.