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Speed Control Analysis of Brushless DC Motor Using PI, PID and Fuzzy-PI Controllers

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ABSTRACT- Brushless DC Motor (BLDC) are relatively new in the industry in comparison to DC motor and induction motor. Conventional controllers like PI, PID are easy to implement but they are not as good as a Hybrid Fuzzy-PI controller for smooth operations. In this paper with the help of MATLAB/SIMULINK, speed response of BLDC motor drive system has been done using PI, PID and Fuzzy-PI controller.

Keywords: BLDC motor, PI, Fuzzy-PI, PID, speed control, converter.

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1. INTRODUCTION

Brushed DC motors were invented in the 19th century and they are still used widely around the world according to the nature of work. The production of torque in a motor happens basically because of the action of the magnetic field by the rotor and stator. There can be one or both working as electromagnets, made of a coil of wire wound around an iron core. The DC creates a magnetic force providing the ingredients which make the running of the motor shaft. A BLDC Motor works quite in a similar fashion to DC Motor, in that the permanent magnet is moving and the current-carrying coil is fixed. When the source supplies power to the stator it becomes an electromagnet and although the source is DC in nature because of the switching it generates an AC Voltage waveform and due to the magnetic interaction between the electromagnet the motor rotates because the North and South poles of the permanent magnet rotor align with the stator poles. The advantage associated with BLDC motors are, better dynamic response, better speed and torque characteristics, more efficiency, high weight to torque ratio [1]. Any motors be it dc motor, induction motor or BLDC motor need to be operated at a desired speed. Speed controllers are used for the controlling the speed of BLDC motor drive system. PI controllers are easy to implement, improves to overall stability. PI controller reduces the steady state error as well. However, it brings disadvantages like sluggish response during sudden change in load and high value of overshoot. PID controllers are easy to implement makes the response of the system smooth however they have a few disadvantages like a) Feedback controller- The continuous parameters of a feedback system are the difficulties with PID controllers. Implementation is frequently responsive and compromised due to a lack of direct process understanding. Nonlinear systems are used for PID controllers. As a result of this, the over-damped nature is reduced, but the system performance is also hampered. Fuzzy Logic based speed control offers high efficiency in electrical drive system. With the combination with other traditional controllers fuzzy Logic Controller can be made very robust to the load variations [2]. BLDC motor suffers negative impact on its performance due to disturbances in load and variation in parameters because of its non-linear nature. [3]

2. PERMANENT MAGNET BLDC MOTOR

Figure 1 shows the equivalent circuit of BLDC motor. The circuit equations in matrix form for three phase BLDC motor is [4]:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} I_a & I_{ab} & I_{ac} \\ I_{ba} & I_a & I_{bc} \\ I_{ca} & I_{cb} & I_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

Here phase winding voltages are shown by V_{an}, V_{bn} and V_{cn}, R_s is stator winding's resistance per phase, while phase currents are shown by I_a ,I_b and I_c.

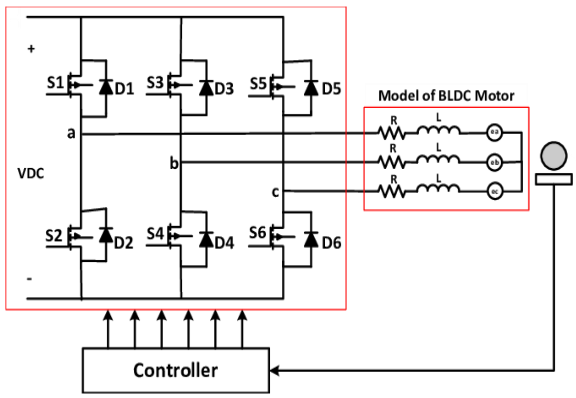

Figure 1: BLDC motor equivalent circuit [5]

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The torque generated is shown as:

$$T_e = \frac{(e_{an}i_a+e_{bn}i_b+e_{cn}i_c)}{\omega_r} \quad (2)$$

Here e_{an} , e_{bn} & e_{bn} represents induced EMF and i_a , i_b & i_c represents input currents in phases a, b and c respectively, angular velocity is represented by ω_r.

3. CONTROLLER STRUCTURES

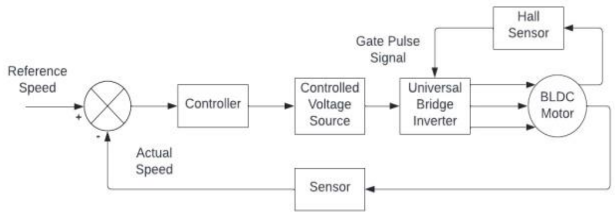

Figure 2: BLDC motor block diagram

Figure 2 demonstrates three phase BLDC drive system's block diagram. When a voltage is given to BLDC motor, the rotor starts rotating, the output .The reference speed is used to analyse speed. Their disparity is reported to the controller. The controller's output is supplied to the controlled voltage source which produces a voltage fed to universal bridge inverter. The universal bridge inverter converts dc voltage to three phase ac voltage and BLDC motor get this voltage.

PI controllers are widely used in industry because they are easy to implement but they generate high overshoot and settling time. To eliminate this problem PID controllers are used they perform better with respect to overshoot and settling time but they are a bit difficult to implement they show poor performance in non-linear systems. For later comparison purpose, Fuzzy-PI is performed which further reduces overshoot and settling time and overshoot.

3.1 PI Controller

PI Controller usually eliminates any steady state error and it cannot decrease rise time and predict future error or oscillations [6]. *Figure 3* represent PI controller's block diagram.

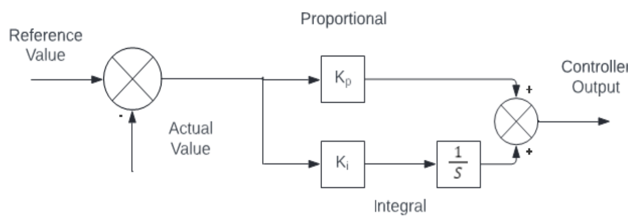

Figure 3: Block diagram of PI controller [7]

PI controller's transfer function is,

$$C_s = K_p + \frac{K_i}{s} \quad (3)$$

Where K_p is represents proportional gain and K_i represents integral gain.

Greater the proportional gain more system will be unstable moreover, a low value proportional gain means that the set point would not be reached by the system. So, that is why gain obtained from PI is tuned to obtain a desired level of speed.

The proportional reduces system's sensitiveness whereas the steady state error is reduced by the integral component.

3.2 PID Controller

Then to decrease the settling time and overshoot, PID controller is used. *Figure 4* represents PID controller's block diagram.

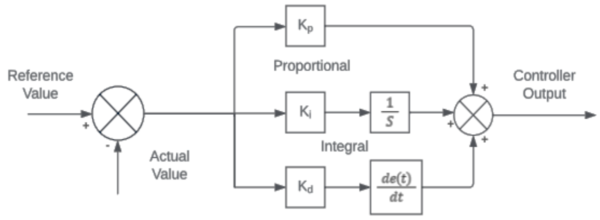

Figure 4: Block diagram of PID controller [8]

This controller has 0% steady-state error, no oscillations, short rising time and improved stability. Proportional while maintain the steady state error makes the system responsive. Integral helps in reducing the steady state error but cannot predict the future behaviour of error. A derivative gain component is added to PI controller to improve oscillations and overshoot in the output response of the system.
The transfer function of PID controller is,

$$C_s = K_p + \frac{K_i}{s} + K_d s \quad (4)$$

K_d represents the derivative gain.

3.3 Fuzzy Logic Controller (FLC) Structure

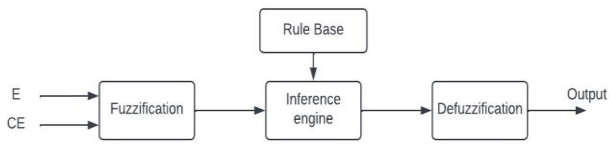

Figure 5: Fuzzy logic controller [9]

Fuzzy logic is simply advancement of the conventional Boolean logic. It represents the degree of event in continuous way so, that it gives the decision according to the way of event movement. It's really helpful in decision making abilities in machine application. These functions are commonly used in control applications, using a set of fuzzy logic rules, a reference and measurement are supplied in and some actuating signal is produced. There are basically two approaches to FLC [10]. Mamdani and Takagi and Sugeno's approach. It's advantages are cheaper, robust, customizable, reliable and efficiency.

a. **Fuzzification:** In this process crisp values are converted into fuzzy linguistic values.
b. **Knowledge Base:** In order to attain the control goal, a set of expert control rules (knowledge) must be followed.
c. **Defuzzification unit:** It produces the needed crisp values by converting the results of fuzzy reasoning system.[11]

3.4 FLC in Combination with PI Controller

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PI controller is generally used to get rid of the disadvantage of FLC. FLC is in command when it is at a distance from point of operation and terminates the undershoots and overshoots occurrence in drive response.

4. SIMULATION RESULT

MATLAB/SIMULINK simulations were done on a BLDC motor system to verify the described control strategies. Parameters used in these systems are given in *Table 1*.

Table 1: Motor Parameters

Parameters	Value
Power	320 W
Stator Phase Resistance	0.7 Ω
No. Of Pole Pairs	4
Torque Constant	0.84 Nm
Inertia(J)	0.8m Kgm^2
Back EMF	Trapezoidal

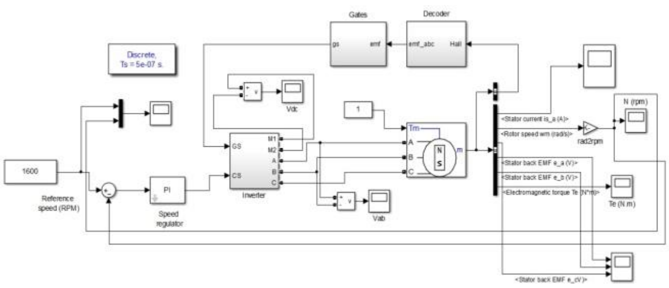

Figure 6: BLDC motor's speed response with PI controller in SIMULINK

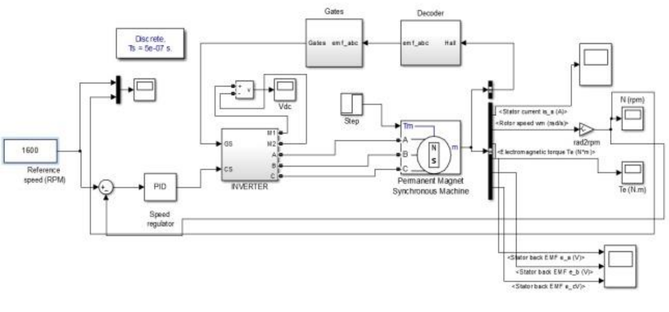

Figure 7: BLDC motor's speed response with PID controller in SIMULINK

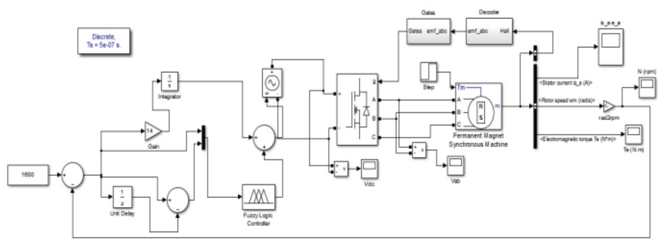

Figure 8: BLDC motor's speed response with Fuzzy- PI controller in SIMULINK

Figures 6, 7 and 8 shows the SIMULINK diagram of PI, PID and Fuzzy in combination with PI controller, based BLDC motor drive system respectively. Their speed responses have been shown in *Figure 10 and Figure 11*. In this paper the reference speed has been kept at 1600 rpm.

FLC consist of two inputs first is error(E) and second is change in error (C_Error). It consists seven membership function of Triangular type because of its simplicity in use. Thus 49 rules are made on MAMDANI-type FIS. MOM (Mean of Maximum) method for defuzzification is used for the output.

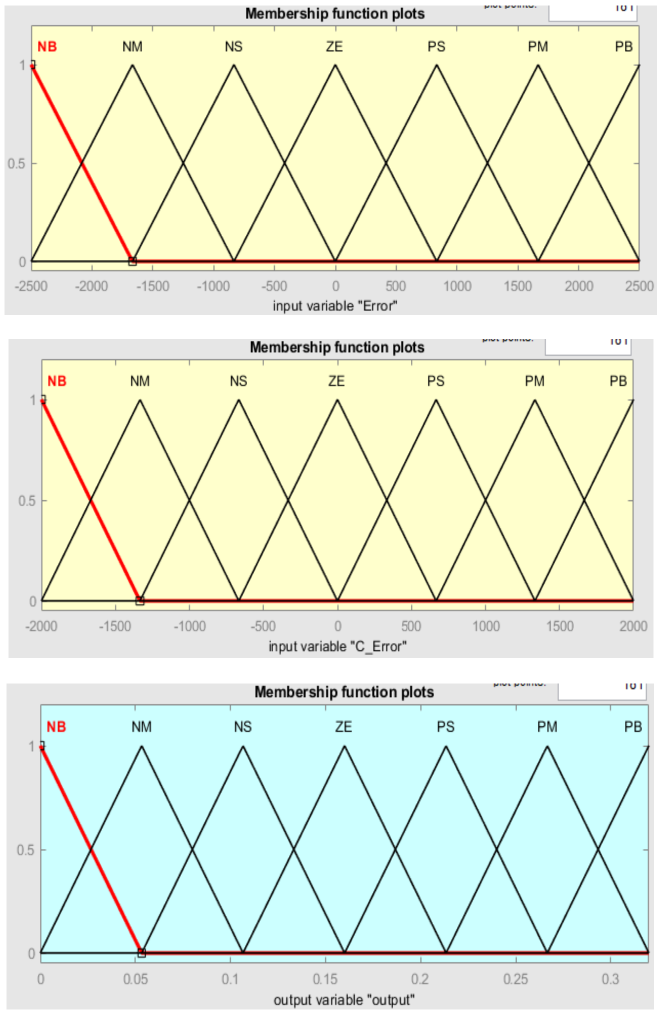

Figure 9: Input (Error, C_Error) and output (V) membership functions of fuzzy logic controller

Table 2: FLC Rules Table [12]

C_Error \ E	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

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In *Table 2* the linguistic levels are described as positive big (PB), positive small (PS), positive medium (PM), negative medium (NM), negative small (NS), negative big (NB), zero (ZE).

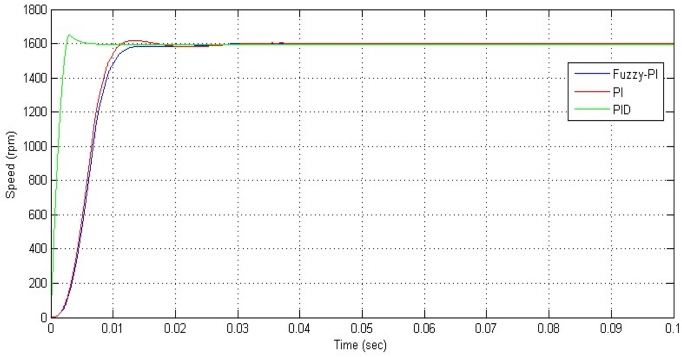

Figure 10: BLDC motor's speed response with Fuzzy- PI, PI and PID controller at 1600 rpm under no-load

Figure 10 shows the speed response of the BLDC motor with Fuzzy-PI, PI and PID controller under no-load condition of 1600 rpm. PI, PID overshoot are 1.1229%, 3.6004% respectively their settling time are 0.0105 sec, 0.00391 sec respectively whereas Fuzzy-PI overshoot and settling time are 0.1567%, 0.0122 sec respectively.

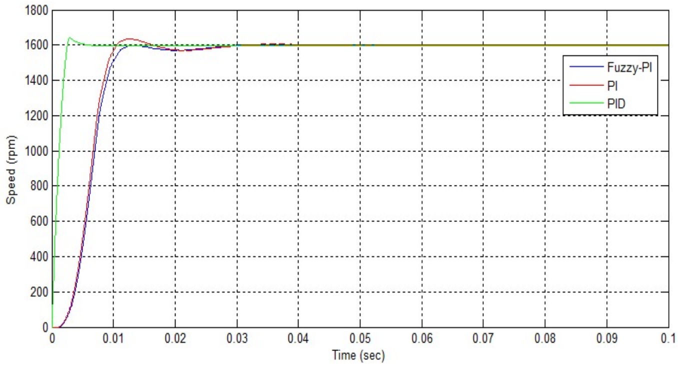

Figure 11: Speed Response of the BLDC motor with Fuzzy- PI, PI and PID controller at 1600 rpm under 1N-m load

Figure 11 shows the speed response of BLDC motor using Fuzzy-PI, PI and PID controller at a reference speed of 1600 rpm under 1N-m. PI settling time is 0.0133 sec and overshoot is 2.1900%. PID settling time and overshoot is 0.0036 sec and 3.0214 % respectively. Fuzzy-PI settling time is 0.0110 sec and overshoot is 0.3041%. At 0.02 second to 0.03 second there is presence of undershoot, this happened because of the action of the constant load which is applied to the BLDC motor. In both PI and Fuzzy-PI controller-based BLDC motor drive system, there is undershoot but in Fuzzy-PI there is least overshoot and from *Table 3* it can be seen that this hybrid Fuzzy-PI offers least steady state error among all the controllers. Hence, Fuzzy-PI makes system response very smooth compared to other two controllers.

Table 3: Various Controllers' Performance Comparison [13]

No- Load			
Controller	PI	PID	Fuzzy-PI
Overshoot %	1.1229	3.6004	0.1567
Settling time(sec)	0.1005	0.0039	0.0122
Steady state error (rpm)	2	6	1
At Load (1N-m)			
Controller	PI	PID	Fuzzy-PI
Overshoot %	2.1900	3.0214	0.3041
Settling time(sec)	0.1133	0.0036	0.0110
Steady state error (rpm)	2	6	1

From the *Table 3* it can be said that under no-load and loaded condition of 1Nm PID controller has highest overshoot% but less settling time, and PI follows just opposite of PID controller. Whereas Fuzzy-PI with least overshoot%, a low value of settling time and least steady state error clearly marks the impression of being better speed controller than other two usual controllers. A normal FLC would settle with a large speed error during load variations.

5. CONCLUSION

In many power electronics devices BLDC motor has upper edge over DC motor due to better speed and torque characteristics, less noisy and high efficiency. Like other motor it too needs speed controllers for smooth operations. PI, PID and Fuzzy-PI controllers have been discussed. With the help of simulations under no-load and loaded (1Nm) conditions it can be said that for a smooth operation Fuzzy-PI is best controller due to its less value of both overshoot% and settling time, and having least steady state error.

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