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Performance Analysis of Direct Torque Controlled BLDC motor using Fuzzy Logic

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ABSTRACT

The Brushless DC motor (BLDC) control is used in many of the applications as it is small in size and with low power which can drive in high speed and lighter compared to other motors.The electric vehicles are built with BLDC motors and also in ships, aerospace etc., The control of BLDC motors is done with sensors like hall effect sensor for sensing the positions. The speed control can be done with normal PI and PID controllers. Direct torque control (DTC) of the BLDC motor is important in many applications. In this paper BLDC motor is controlled with DTC using PI, PID and Fuzzy logic control. The comparison of the performance of the motor is analyzed with the Matlab simulation software.

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Nomenclature

T_e	*electromagnetic torque*
P	*number of poles*
L_d, L_q	*direct and quadrature axis inductance*
θ_e	*electrical angle or rotor angle*
ψ_{rd}, ψ_{rq}	*direct and quadrature axis rotor flux linkage*
ψ_{sd}, ψ_{sq}	*direct and quadrature axis stator flux linkge*
i_{sd}, i_{sq}	*direct and quadrature axis stator current*
ψ_{sa}, ψ_{sb}	*alpha and beta coordinate flux linkage*
i_{sa}, i_{sb}	*alpha and beta coordinate stator current*
u_{sa}, u_{sb}	*alpha and beta coordinate stator voltage*
R	*stator resistance*

1. INTRODUCTION

The brushless DC motors are two types. One is sinusoidal and other is trapezoidal electromotive force (EMF). The sinusoidal is known as permanent magnet synchronous machine (PMSM) and trapezoidal is known as permanent magnet brushless DC machine (PMBLDC or BLDC). Many literatures are available on the control of BLDC motor and are discussed as follows.

4,11 The direct torque control is successfully applied and improvement in the performance of the induction machines is analyzed [2, 10]. It is also applied to reduce the torque pulsation in the PMSM machine with vector control strategy [1]. In 1993, linear quadratic controller and load observer is utilized to obtain the robust BLDC motor control system [16]. The direct torque control for BLDC motor drives is implemented to reduce ripples in toque [17]. The 60 degree conduction is generally used for converter in BLDC motor control. Due to this, the created torque ripples can be reduced by hybrid two phase and three phase switching during commutation periods [18]. A new robust method is also presented for reducing the torque ripples [8]. The non-sinusoidal back EMF with two phase conduction mode is used to reduce the torque ripples [3]. Indirect flux control is also used for making the BLDC in high speed operations [19]. A non ideal EMF is used as the feed back and torque ripples are reduced significantly [14]. The direct self control is used in induction motor drive and is also extended for BLDC motor drives to improve the performance [15]. The current lost in the other control methods of BLDC motors are accumulated in combined method of BLDC motor control [5]. To reduce the common mode voltage and increase the reliability a hysteresis torque control method is presented [6]. A sensorless control of BLDC motor is made for reducing the cost [11]. A modeling of hybrid BLDC torque motor is done by Hong in 2010 [4].

The optimal design of slot-less PMBLDC motor is designed with genetic algorithm for performance improvement [9]. And output power optimization is made for five phase BLDC motor [12]. The Z-source inverter is used for Photo-voltaic (PV) maximum power tracking and control of BLDC is also achieved [7]. The number of switches is reduced to four switches as conventionally BLDC works with six-switches [13]. Fuzzy based BLDC control implemented with multilevel inverter [20]. PFC correction of single phase supply loaded with BLDC drive is presented in 2015 [21].

In this paper, the BLDC motor is controller with direct torque control with Proportional-Integral (PI), Proportional-Integral-Derivative (PID) and fuzzy logic controller are used to compare and analyze the transient stability of the motor

2. DIRECT TORQUE CONTROL OF BLDC MOTOR

The influence of mutual coupling between direct and quadrature axis is negated. The electromagnetic torque of the BLDC motor in synchronously rotating dq reference is given in equation (1) [17].

$$T_e = \frac{3}{2}\frac{P}{2}\left\{\left[\left(\frac{dL_d}{d\theta_e}\right)i_{sd} + \left(\frac{d\psi_{rd}}{d\theta_e}\right)i_{sd} - \psi_{sq}\right]i_{sd} + \left[\left(\frac{dL_q}{d\theta_e}\right)i_{sq} + \left(\frac{d\psi_{rq}}{d\theta_e}\right)i_{sd} - \psi_{sa}\right]i_{sq}\right\} \quad (1)$$

where,

$$\psi_{sd} = L_d i_{sd} + \psi_{rd} \quad (2)$$

$$\psi_{sq} = L_q i_{sq} + \psi_{rq} \quad (3)$$

Torque equation for BLDC motor can be simplified as

$$T_e = \frac{3}{2}\frac{p}{2}\left(\psi_{sd} i_{sq} - \psi_{sq} i_{sd}\right) \quad (4)$$

in alpha-beta coordinate,

$$T_e = \frac{3}{2}\frac{p}{2}\left(\psi_{sa} i_{sb} - \psi_{sb} i_{sa}\right) \quad (5)$$

where,

$$\psi_{sa} = \psi_{sd}\cos\theta_e - \psi_{sq}\sin\theta_e \quad (6)$$

$$\psi_{sb} = \psi_{sd}\sin\theta_e - \psi_{sq}\cos\theta_e \quad (7)$$

$$i_{sa} = i_{sd}\cos\theta_e - i_{sq}\sin\theta_e \quad (8)$$

$$i_{sb} = i_{sd}\sin\theta_e - i_{sq}\cos\theta_e \quad (9)$$

The flux-linkage observers can be derived as follows [17]

$$\psi_{sa} = \int (u_{sa} - Ri_{sa})\, dt \quad (10)$$

$$\psi_{sb} = \int (u_{sb} - Ri_{sb})\, dt \quad (11)$$

The magnitude and angle of the stator flux can be shown as

$$\psi = \sqrt{\psi_{sa}^2 + \psi_{sb}^2} \quad (12)$$

$$\theta = arctan\left(\frac{\psi_{sb}}{\psi_{sa}}\right)$$

Table 1. shows the switching table of the pulse width modulation. The block diagram for the proposed work is given in Figure 1.

Table 1. Switching Table

Torque (T)	**Flux**	**Sector**					
		I	**II**	**III**	**IV**	**V**	**VI**
1	**1**	V1	V2	V3	V4	V5	V6
	0	V2	V3	V4	V5	V6	V1
	-1	V3	V4	V5	V6	V1	V2
0	**1**	V1	V2	V3	V4	V5	V6
	0	V0	V0	V0	V0	V0	V0
	-1	V3	V4	V5	V6	V1	V2

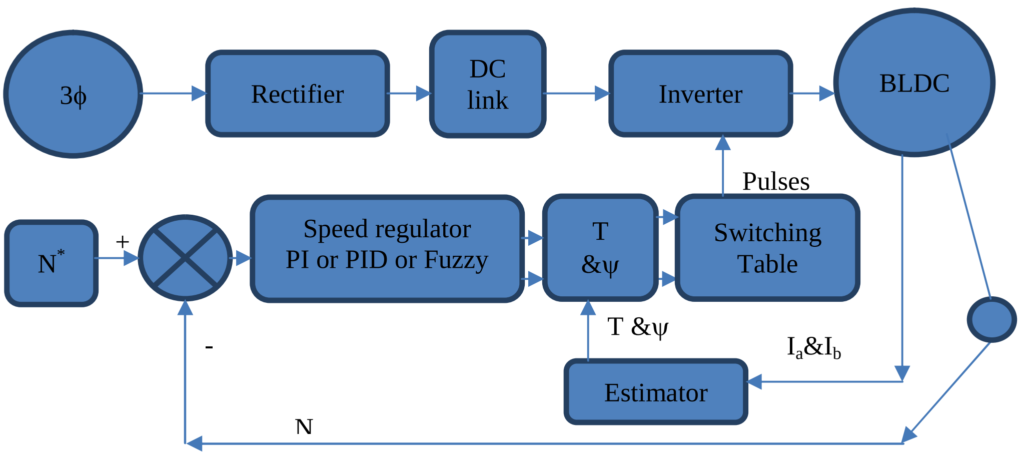

Figure 1. Direct TorqueControl of BLDC motor block Diagram

Table 2 shows the vector table. Where, V is the the vector and '1' shows that switch is on and '0' shows that switch is off.

Table 2. Vector table

Vector	Binary
V0	000000
V1	100001
V2	001001
V3	011000
V4	010010
V5	000110
V6	100100

A) Speed regulator for PI can be expressed as

$$out(t) = K_p(N^* - N) + K_i \int (N^* - N)dt \quad (13)$$

here,

N^* is reference speed and N is the measured speed the difference between both produces the error which should be minimized by the PI controller. The output (out(t)) is the error minimized proposed signal. Kp is the proportional constant and Ki is integral constant.
Similarly, for PID controller can be represented as

$$out(t) = K_p(N^* - N) + K_i \int (N^* - N)dt + K_d \frac{d(N^* - N)}{dt} \quad (14)$$

Here, Kd is derivative constant. The tuning of Kp, Ki and Kd are tuned by manual tuning method.

B) Fuzzy logic based speed regulator

The block diagram for fuzzy logic based speed regulator is shown in Figure 2. The fuzzy logic rules are written by absorbing the performances of the PI controller and PID controller performances. The fuzzy logic rules for the proposed system are given in Table 3.

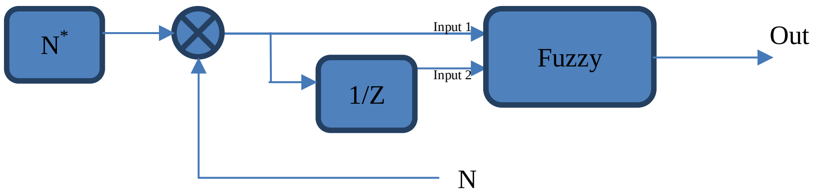

Figure 2. Fuzzy logic control of speed regulation

Table 3. Fuzzy logic rules

err \ ce	**Low**	**Medium**	**High**
Low	Low	High	Medium
Medium	Low	High	High
High	Medium	Low	Medium

Here 'err' is speed error and 'ce' is change in error.

The membership function definition for the input variables "Error in Speed" is shown in Figure 3, "Change in Error" is shown in Figure 4 and the three dimentional surface view of rule based system are shown in Figures 5 respectively.

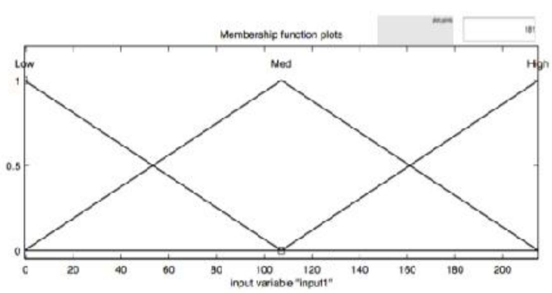

Figure 3. Membership fucniton for Error in Speed

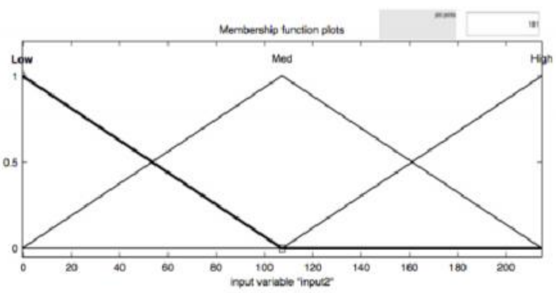

Figure 4. Membership fucniton for Change in Error

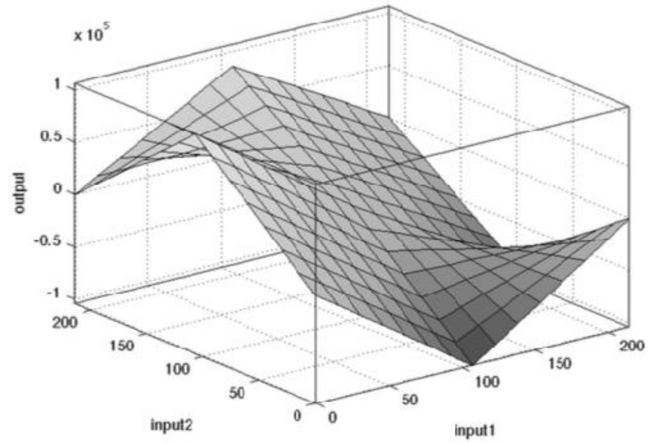

Figure 5. Surface view of the rules of fuzzy inference system

3. SIMULATION RESULTS AND DISCUSSION

The direct torque control of BLDC motor is implemented with simulation tools of MATLAB. The speed regulator is used as PI controller, PID controller and fuzzy logic control seperatedly. The performance analysis is done with speed, current and flux plot. The dynamic performance of the DTC control with BLDC motor is shown Figure 6.

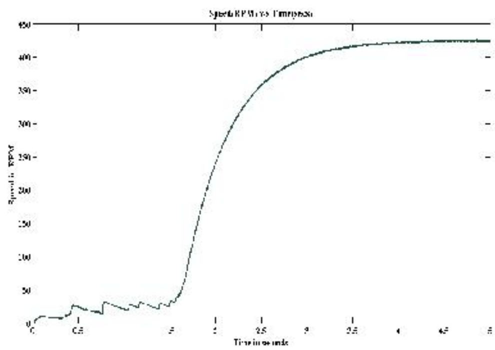

Figure 6. Speed curve for PI controller based speed regulator

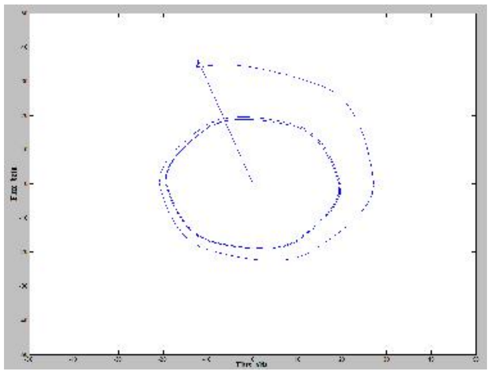

Figure 7. Flux curve of the DTC control of PI controller based speed regulator Figure

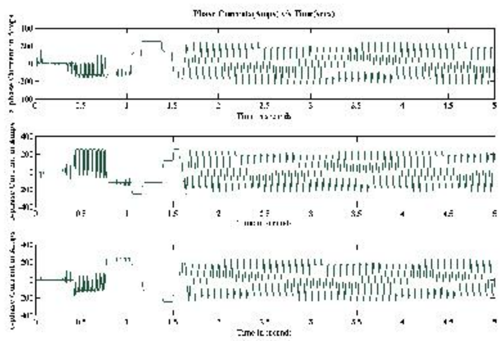

Figure 8. Phase currents of the BLDC motor with PI controller

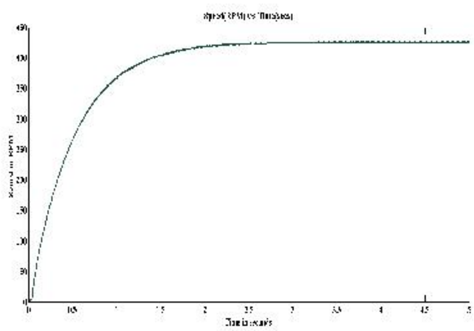

Figure 9. Speed curve with PID controller based speed regulator

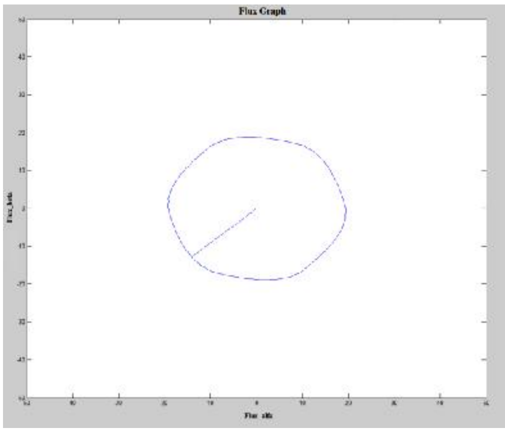

Figure 10. Flux curve with PID controller

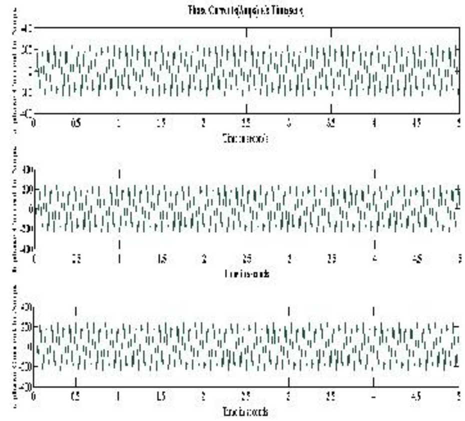

Figure 11. Phase current waveform of BLDC with PID Controller

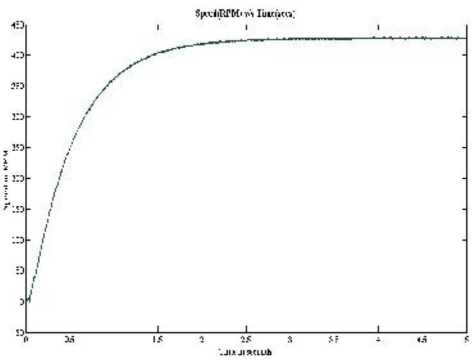

Figure 12. Speed curve for fuzzy logic

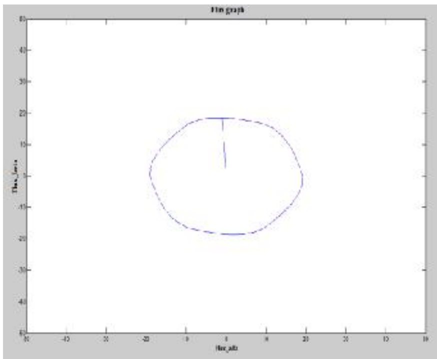

Figure 13. Flux curve for Fuzzy control

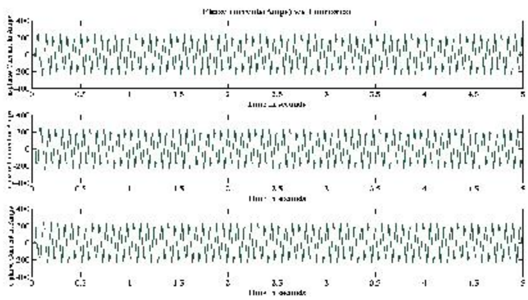

Figure 14. Phase current of BLDC motor with Fuzzy (Green) controller

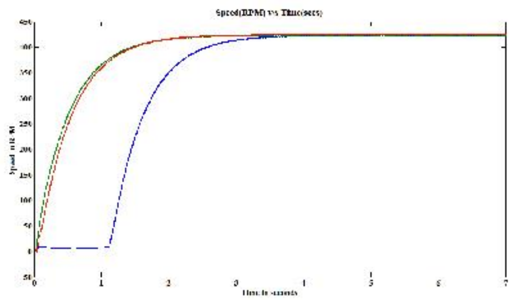

Figure 15. Speed curve of PI (Blue), PID (Red) and Fuzzy logic control

Figures 6 shows the speed of the motor when it is controlled with PI regulator, figure 7 shows the flux curve of the motor and figure 8 shows the current waveforms of the motor with PI controller as speed regulator. The speed of the motor takes at-least 3.5 sec to settle on the set speed this is due to the properties of the PI controller. And flux curve also initially distorted and it is on the correct path. Figures 9 shows the speed curve of the motor when it is connected to PID controller, figure 10 shows the flux curve of the motor when it is connected to PID speed regulator and figure 11 show the stator current wave forms of the motor when it is connected with the PID controller. The speed curve got some betterment and it is settled at 2.5 sec. and other flux curves and current curves are perfect. Figures 12 shows the speed cucrve of the motor with fuzzy speed regultor, figure 13 shows the flux curve of the motor with fuzzy controller and figure 14 shows the stator currents of the BLDC drive with Fuzzy logic controller. The speed curve settled at nearly 2.3 sec and the flux and current curve are better compared to the PI and PID controllers. So fuzzy logic gives better results compared to the PI and PID controllers.

4. CONCLUSION

The analysis of the direct torque control of BLDC motor with its dynamic performance is analyzed by replacing the speed regulator as PI, PID and Fuzzy controller. The PI and PID controllers, which are tuned manually gives results with time delay. It takes more time to achieve steady state. Using a fuzzy logic controller can minimize this time delay. And it can make the system stable faster. The rules are taken with all the three controllers and the PI and PID gives steady state at 3.5 sec and 2.5 sec respectively. And the fuzzy results are obtained well with 2.3 secs.

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