Performance Evaluation of FuzzyPID Controller for Speed Control of Brushless DC Motor Drive

Muhammad Firdaus ZAINAL ABIDIN, Dahaman ISHAK and Anwar Hasni ABU HASSAN
School of Electrical and Electronics Engineering, Universiti Sains Malaysia, Engineering Campus
14300 Nibong Tebal, Penang, Malaysia. Tel : +604-5996006 Fax: +604-5941023
m.firdausza@gmail.com, dahaman@usm.my, eeanwar@usm.my

Abstract— *This paper presents a comprehensive evaluation of FuzzyPID controller by providing an in-depth comparison with PID controller for speed control of permanent magnet brushless DC motor. Motor speed responses are studied for a variety of operating conditions including response to small and large step speed reference change, and response to step load change. Simulation results are further validated with the experiment. The experimental results proved that FuzzyPID controller provides a superior speed response compared to PID controller with faster rise time, faster settling time and minimize the amount of overshoot. The is achievable since the FuzzyPID controller is able to continuously tune the gain parameter online, resulting in more robust motor operation for both transient and steady-state condition.*

Keywords—*PID; Fuzzy; Hybrid Controller; BLDC Motor; Speed Control;*

1. INTRODUCTION

The development of motor speed controller has always been increasing in terms of number as well as the level of complexity. The technological advancement in the capability of modern microcontrollers, power electronics converters and state of the art of motor design, raises the demand for more comprehensive solutions for better control and efficiency. Electric motors have broad applications in many areas such as manufacturing industry, transportations, medical and household electrical appliances, powering a variety of equipment including wind blowers, water pump, compressors, machine tools, etc. Among the electric motors, the permanent magnet BLDC motors are very popular because of their high efficiency, high power factor, silent operation, compact form, reliability and low maintenance which make them widely used in many applications [1]. Apart from that, a standard approach for speed control in industrial drives is to use a Proportional, Integral and Derivative (PID) controller. Nevertheless, PID controller has some weakness in controlling the nonlinear system [2]. Hence, recent developments in technology have brought into focus a possibility of shifting from the conventional PID controller to the artificial intelligent controller such as Fuzzy Logic Control (FLC) [3]. However, PID controller remains a valid approach to implementing a feedback control system. When the nonlinearities of the system are the major issues in motor control, there is an option to improve the PID control strategy rather than to replace with complicated dynamic models which require sophisticated control strategies. Thus, FuzzyPID controller can be one of the alternative solutions for improving the speed control of BLDC motor.

From the literature review, we notice that the existing works on FuzzyPID controller for speed control of PM BLDC motor as reported in [6], [9], [10] and [11] are only based on simulation study. Thus, in order to have a comprehensive analysis, in this research, we also conducted the experiments under various motor operating conditions to further support and validate the simulation results.

2. MATHEMATICAL MODEL OF BLDC

PM BLDC motor can be modeled in the 3-phase abc variables which consist of two parts. The first is an electrical part which estimates the electromagnetic torque and current of the motor. The other is a mechanical part which governs the motor's rotating motion. Refer to Fig. 1, the electrical part of PM BLDC motor can be represented in matrix form as follow [4]:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_a & L_{ab} & L_{ac} \\ L_{ba} & L_b & L_{bc} \\ L_{ca} & L_{cb} & L_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

where V_{an}, V_{bn} and V_{cn} are the phase winding voltages, R_s is the resistance per phase of the stator winding, while i_a, i_b and i_c are the phase currents.

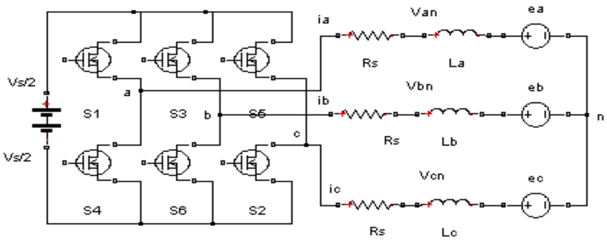


Fig. 1. Equivalent circuit of BLDC Motor

If there is no change in rotor reluctance with angle because of a non-salient rotor, and assuming three symmetric phases, the following are obtained:

$$L_a = L_b = L_c = L \tag{2}$$

$$L_{ab} = L_{ba} = L_{ac} = L_{ca} = L_{bc} = L_{cb} = M \tag{3}$$

Substituting equations (2) and (3) into equation (1) gives the PM BLDC model as:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = R_s \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{4}$$

From equation (4), phase voltage for phase A, V_{an} can be derived as:

$$V_{an} = R_s i_a + L \frac{di_a}{dt} + M \frac{di_b}{dt} + M \frac{di_c}{dt} + e_a \tag{5}$$

$$V_{an} = R_s i_a + L \frac{di_a}{dt} + M \frac{d}{dt}(i_b + i_c) + e_a \tag{6}$$

The stator phase currents are constrained to be balanced and $i_a + i_b + i_c = 0$. So, equation (6) can be expressed as:

$$V_{an} = R_s i_a + (L - M)\frac{di_a}{dt} + e_a \tag{7}$$

Similarly for phase b and c:

$$V_{bn} = R_s i_b + (L - M)\frac{di_b}{dt} + e_b \tag{8}$$

$$V_{cn} = R_s i_c + (L - M)\frac{di_c}{dt} + e_c \tag{9}$$

Next, add equations (7), (8) and (9), yields:

$$V_{an} + V_{bn} + V_{cn} = R_s(i_a + i_b + i_c) + (L - M)\frac{d}{dt}(i_a + i_b + i_c) + e_a + e_b + e_c \tag{10}$$

As shown in Fig. 1, neutral voltage is referred to the zero reference potential at midpoint of dc-link. So the phase voltages can be expressed as:

$$V_{an} = V_{a0} - V_{n0} \tag{11}$$

$$V_{bn} = V_{b0} - V_{n0} \tag{12}$$

$$V_{cn} = V_{c0} - V_{n0} \tag{13}$$

where V_{a0} , V_{b0} , V_{c0} and V_{n0} are the output phase voltages from the inverter and the potential of the star point referred to the neutral, respectively. In order to avoid unbalance in the applied voltages, a balance three-phase winding with star-connected is considered. This leads to estimate the value of V_{n0} by substituting equations (11), (12) and (13) into (10), and considering the equivalent of phase currents, equation (10) becomes:

$$V_{a0} + V_{b0} + V_{c0} - 3V_{n0} = (e_a + e_b + e_c) \tag{14}$$

Thus, the neutral voltage is equal to:

$$V_{n0} = \frac{V_{a0} + V_{b0} + V_{c0} - (e_a + e_b + e_c)}{3} \tag{15}$$

The developed electromagnetic torque can be expressed as:

$$T_e = \frac{(e_{an} i_a + e_{bn} i_b + e_{cn} i_c)}{\omega_r} \tag{16}$$

The mechanical part of BLDC motor can be modeled as:

$$J \frac{d\omega_r}{dt} + B \omega_r = (T_e - T_l) \tag{17}$$

where J is moment of inertia in kg-m^2, B is frictional coefficient in N-ms/rad, T_e is the electromagnetic torque, T_l is load torque in Nm. The derivative of electrical rotor position θ_r , is expressed as:

$$\frac{d\theta}{dt} = \frac{P}{2}\omega_r \tag{18}$$

where P is number of pole, ω_r is the rotor speed in mechanical rad/sec and θ is the electrical rotor position in electrical radian.

3. SIMULATION STUDY

The model of speed controller has been realized using the Simulink toolbox of the MATLAB software. The main function of speed controller block is to provide a reference speed which in turn is converted to reference current and is fed to reference generator. The output of the speed controller is limited to a proper value in accordance with the motor rating to generate the reference speed. The speed controllers realized in this study are PID controller and FuzzyPID controller, respectively.

*A. **PID Controller***

The performance specifications of the systems such as rise time, percentage of maximum overshoot, settling time and error steady state can be improved by tuning parameter values K_p, K_i and K_d for the PID controller, because each component has its own special purpose as shown in Fig. 2. The PID controller can be represented as [5]:

$$y(t) = \left[K_p e(t) + K_d \frac{d(e)}{d(t)} + K_i \int_0^t e(t)d(t)\right] \quad (19)$$

where *y(t)* is the output of the PID controller, K_p is the proportional gain, K_i is the integral gain, K_d is derivative gain and $e(t)$ is the instantaneous error signal.

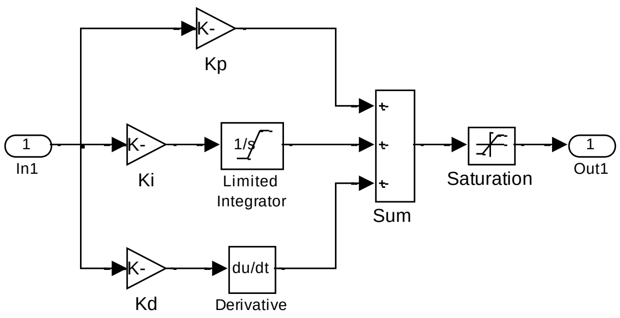


Fig. 2. Block diagram of PID control system

B. FuzzyPID Controller

The description of FuzzyPID controller is the three parameters K_p, K_i and K_d of PID controller which are tuned by using Fuzzy Logic Controller (FLC) [6, 7]. The coefficients of the conventional PID controller are not often properly tuned for the nonlinear plant with unpredictable parameter variations. Hence, it is necessary to automatically tune the PID parameters. The structure of the FuzzyPID controller is shown in Fig. 3.

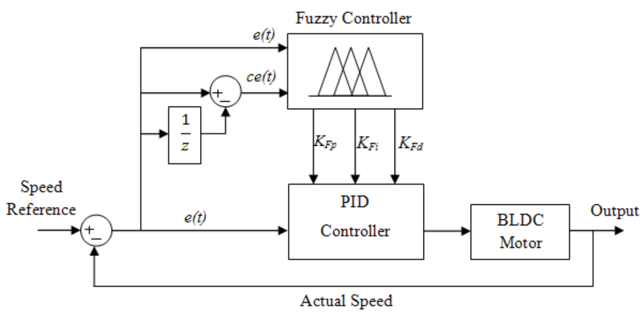


Fig. 3. Structure of FuzzyPID controller

The PID parameters are tuned by using fuzzy inference, which provide a nonlinear mapping from the error and derivation of error to PID parameters. With regarding to the fuzzy structure in Fig. 3, there are two inputs to the fuzzy inference block which are error *e(t)* and change of error *ce(t)* [8], while the three outputs are K_{Fp}, K_{Fi} and K_{Fd}. Speed error is calculated after comparing the reference speed, ω_{ref} with the actual speed, ω_{act}. Based on equation (20), the variable values of K_p, K_i and K_d are added up with K_{Fp}, K_{Fi} and K_{Fd} respectively which had been calculated from the fuzzy block and these values K_{Fp}, K_{Fi} and K_{Fd} vary dynamically and continuously online during the motor operating conditions. So it can tune the conventional PID parameters online in order to adapt the dynamic change in the motor drive system. FuzzyPID can be expressed with the following equation:

$$y(t) = \begin{Bmatrix} [K_p + K_{Fp}]e(t) + [K_d + K_{Fd}]\frac{d(e)}{d(t)} + \\ [K_i + K_{Fi}]\int_0^t e(t)d(t) \end{Bmatrix} \quad (20)$$

Mamdani model is applied as structure of fuzzy inference with some modification to obtain the best values for K_{Fp}, K_{Fi} and K_{Fd}. By having five and three membership functions for speed error and change of speed error respectively, the total number of rules is equal to 15. The fuzzy rule base is shown from Tables 1-3. The membership function consists of five sets which are NB: Negative Big, NS: Negative Small, ZE: Zero, PS: Positive Small and PB: Positive Big.

Table 1
The Fuzzy Rule-Base for K_{Fp}

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

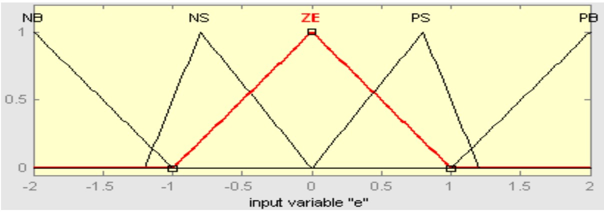
Table 2
The Fuzzy Rule-Base for K_{Fi}

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

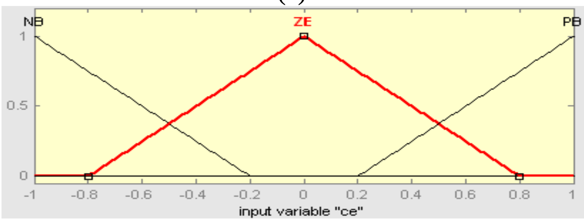
Table 3
The Fuzzy Rule-Base for K_{Fd}

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

Through many simulation runs, FLC were fine-tuned manually based on the rule designed, so that the best possible response is obtained. Fig. 4 and Fig. 5 illustrate the membership functions of the optimized FLC tuned PID variables, which are of unequal widths and asymmetrically positioned peaks.



(a)



(b)

Fig. 4. Membership function of (a) error e(t), (b) change of error ce(t)

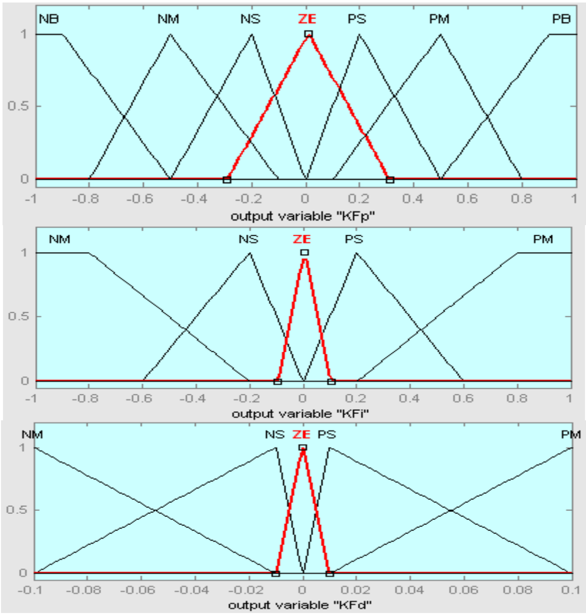


Fig. 5. Membership function of K_{Fp}, K_{Fi} and K_{Fp}

The simulation parameters of BLDC motor are summarized in Table 4.

Table 4
Simulation parameter of BLDC motor

Parameters	Value
Pole-pair number, *p*	5
Supply voltage, V_{dc}	48 V
Armature resistance, R_s	4.03 ohm
Self inductance, *L*	4.6 mH
Mutual inductance, *M*	-0.35 mH
Motor inertia, *J*	0.00033 kgm^2
Emf constant, *K*	0.76 ($Vs/rads^{-1}$)

The PID controller is designed first, while the FuzzyPID controller is designed next. The PID controller was tuned by using Ziegler-Nicholas tuning method to yield an optimum speed response with minimum settling time and overshoot. After some manual fine tuning through simulation, the final controller parameters for PID are K_p = 0.1, K_i = 4 and K_d = 0.0004. For FuzzyPID controller, the same values of PID parameters are used and will be integrated with Fuzzy Logic Controller.

The simulation study is performed in two cases which include the speed response to the step change of load at constant speed and the speed response to step change of reference speed at constant load.

4. SIMULATION RESULTS AND ANALYSIS

Case 1: Step change of load from 2Nm to 3Nm at constant reference speed 600rpm

Initially the motor was loaded with 2Nm load. Then the motor was run at speed reference 600rpm. At t=0.15s, the load was increased to 3Nm. Fig. 6 shows the simulation results of speed response for PID controller and FuzzyPID controller. From the simulation results, it is observed that the FuzzyPID controller has the faster rise time and settling time during start-up compared to the PID controller. At t = 0.15s, the load was increased from 2Nm to 3Nm which caused the speed to undershoot momentarily. This happened because during the transition period when the motor is loaded with higher load, the previous amount of current is not enough to support the increasing load. So the motor speed undershoot for a moment and then, it managed to get back to the targeted speed by increasing the amount of phase current. PID controller has slightly larger amount of undershoot compared to FuzzyPID controller, however, both controllers managed to track the reference speed with smaller settling time.

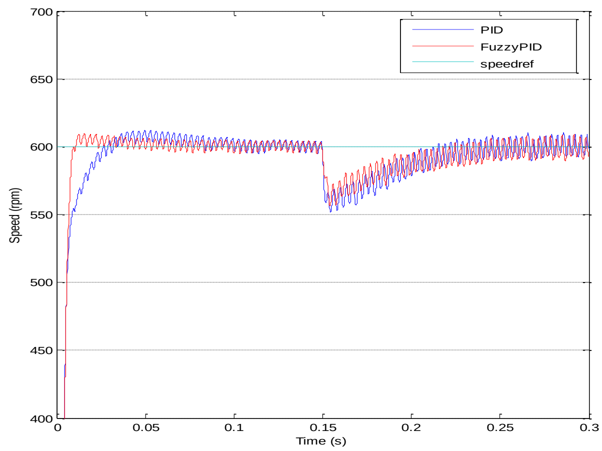


Fig. 6. Comparison of speed response between PID controller and FuzzyPID controller for Case 1

Case 2: Step change of speed reference from 400rpm to 600rpm at constant load 3Nm

The simulation analysis was continued to observe the performance of speed response against a step change of speed reference at constant load. During start-up, the speed reference was set at 400rpm with load 3Nm. At t=0.15s, the speed reference was increased to 600rpm. Fig. 7 shows the simulation results of speed response for PID controller and FuzzyPID controller respectively

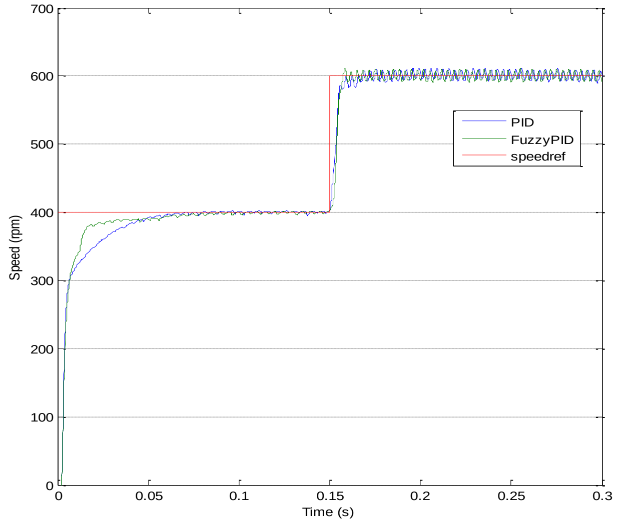
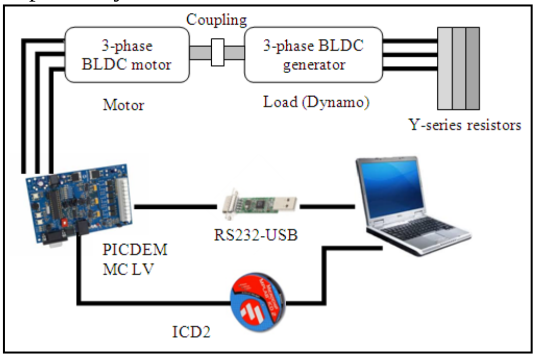


Fig. 7. Comparison of speed response between PID controller and FuzzyPID controller for Case 2

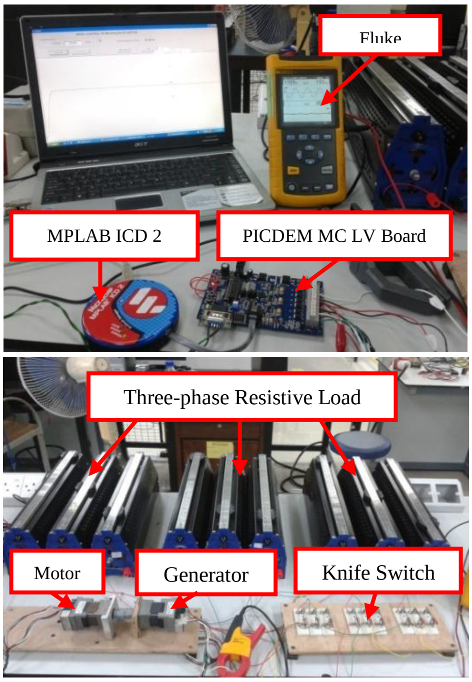
The results illustrated in Fig. 7 shows that both controllers provide approximately the same performance during the step change of speed reference. PID controller manages to adapt the small step changes in speed reference with no overshoot, fast rise time and short settling time during the transient. Similarly, almost the same results were obtained by FuzzyPID controller. However, there is still a gap which FuzzyPID manages to fill in to get a slightly better performance since FuzzyPID controller provides faster rise time during the start-up from standstill as clearly shown in Fig. 7.

5. EXPERIMENTAL SETUP

The research is continued with the experiment in the laboratory with hardware implementation. Fig. 8(a) shows the block diagram of the experiment which consists of a controller board, three-phase BLDC motor, three-phase PM generator, three-phase Y-connected resistive load and a PC. The experiment was carried out using PICDEM MC LV Development Board manufactured by Microchip Technology. The the source codes for PID control and FuzzyPID control algorithm were programmed and embbed into the dSPIC30F2010 microcontroller. Fig. 8(b) shows the experimental setup for evaluating the performance of both speed controllers. The PM brushless DC motor was coupled to the PM generator. Three-phase Y-connected resistive loads were connected to the output of the generator. Three sets of knife switch were used to vary the loads. The resistive loads were connected in such a way that the net load at the generator can be instantaneously changed from initially 16.5Ω to 9.3Ω, and finally to 3.8Ω per phase with different positions of the knife switch. The speed response of the motor was displayed in the PC via RS232 cable. The input of PID controller is the speed error. The Hall sensors are used to get the feedback of the motor speed. The PID controller adjusts the duty cycle of the PWM to get the actual speed close to the reference speed. The PID controller was initially tuned using Ziegler Nichols tuning method. Subsequently, the gains were tuned manually around the calculated to optimize the performance of the motor. Final parameter values for the PID controller: proportional, integral and derivative gains are 350, 0.5 and 0.045 respectively.



(a) Block diagram



(b) Experiment Setup

Fig. 8. Experiment and Measurements

To implement FuzzyPID algorithm in the microcontroller, the same source code of PID controller has been modified by adding the fuzzy algorithm, yielding a FuzzyPID control system. A standard form of Fuzzy Logic control structure normally uses two inputs which are error, *e* (for example, how close is the actual speed to the reference speed) and change in error, *ce* (for example how fast is the measured speed approaching the desired speed). So in this research, the error is the difference between actual speed to the desired speed, while change in error is the difference between the previous error to the current error. Five membership functions for speed error and three membership functions for change of speed error with overlap, triangle shape and same width are used for each input variable, so that 15-rules are created.

The experiments were conducted in several cases to observe the performance of the speed response of the BLDC motor between PID and FuzzyPID controllers respectively. Most of the experiments are focusing on the speed reference of 2000rpm since the PID controller has been tuned at this reference speed. However, there are two speed references which are 20% higher and lower of the 2000rpm which have been selected to verify the performance of the speed response.

6. EXPERIMENTAL RESULTS AND ANALYSIS

Case A: Response to 20% step increase / decrease of the speed command at no load

The system initially operates in steady state at reference speed 2000rpm with the PM generator terminals were left opened. A step speed command of increase and decrease, equal to 20% of the previous reference setting is applied 5s after start-up. The results are shown in Fig. 9 and Fig. 10 for increase and decrease of speed command respectively. The response obtained with the FuzzyPID controller is much better in terms of both the reduction of overshoot and increase of settling time. Although the rise time of the PID controller is slightly faster than FuzzyPID controller, but it resulted in an overshoot during the transient.

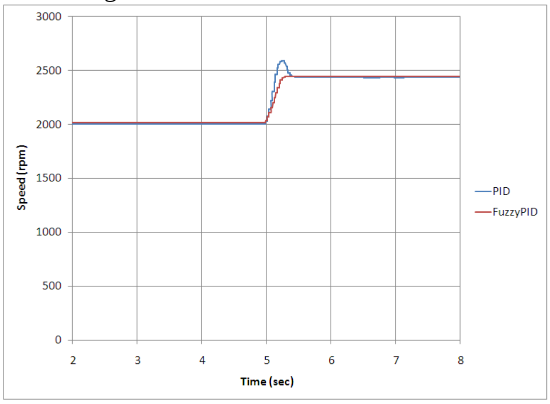


Fig. 9. Speed response to 20% step speed increase at no load for PID and FuzzyPID controllers

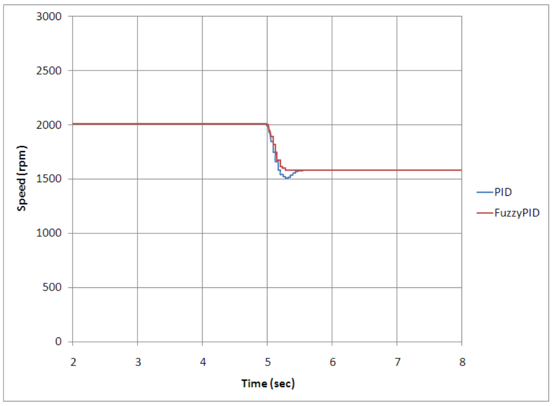


Fig. 10. Speed response to 20% step speed decrease at no load for PID and FuzzyPID controllers

Case B: Response to 20% step increase / decrease of the speed command at 16.5Ω load

The same experiment as described in Case A was repeated by connecting the terminals of the PM generator with 16.5Ω load per phase. At time equal to 5s, a step speed command of increase and decrease, equal to 20% of the previous steady-state 2000rpm is applied respectively. The results illustrated in Fig. 11 and Fig. 12 show that both controllers provide approximately the same performance for both tests except FuzzyPID controller provides a slightly faster rise time and settling time during the increase of the speed reference setting. PID controller manages to adapt the step changes in speed reference with no overshoot during the transient as the same result obtained by FuzzyPID controller. However, there is still a gap which FuzzyPID manages to fill in to get a slightly better performance which indicates that FuzzyPID offers the best speed response with faster rise time and settling time.

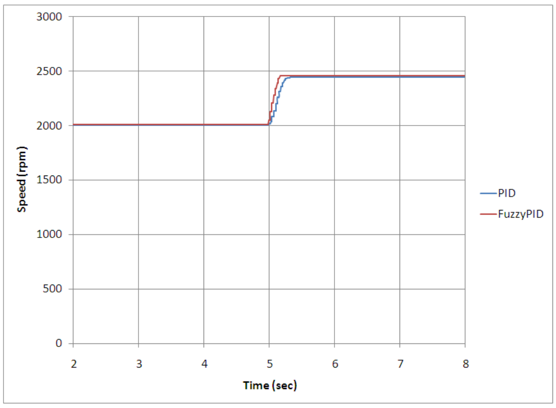


Fig. 11. Speed response to 20% step speed increase at 16.5Ω load for PID and FuzzyPID controllers

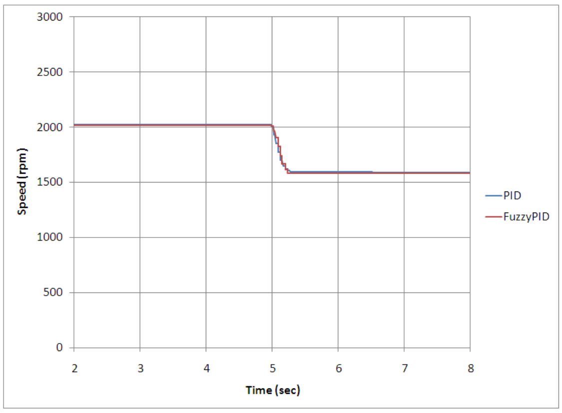


Fig. 12. Speed response to 20% step speed decrease at 16.5Ω load for PID and FuzzyPID controllers

Case C: Response to step increase / decrease of load at reference speed 2000rpm

In this section, resistive loads of 3.8Ω, 9.3Ω and 16.5Ω are applied in a stepwise manner i.e. being increased and decreased by connecting the PM generator terminals to a set of Y-series connected resistive load at speed reference setting

2000rpm. The results of the speed response are shown in Fig. 13 and Fig. 14 where the loads being increased and decreased respectively. For instance of increasing load in stepwise manner, the motor will operate from idle condition to reference speed with generator connected to 16.5Ω load per phase. Later, at time interval of 5s, the load was increased by using 9.3Ω per phase. At time interval of 10s, the generator load was further increased by using 3.8Ω per phase. Therefore, at time interval of 5s and 10s, the load was increased and decreased continuously.

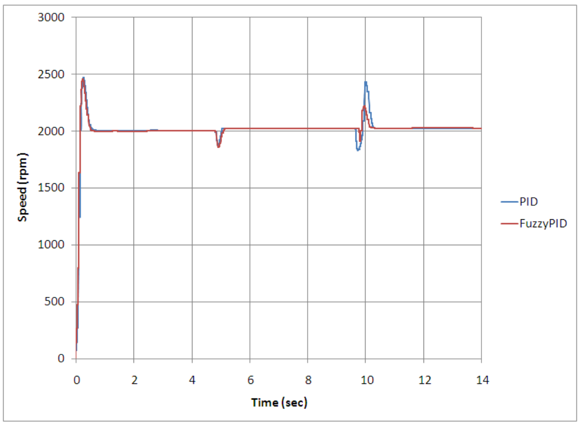


Fig. 13. Speed response to step load increase at every 5s for PID and FuzzyPID controllers

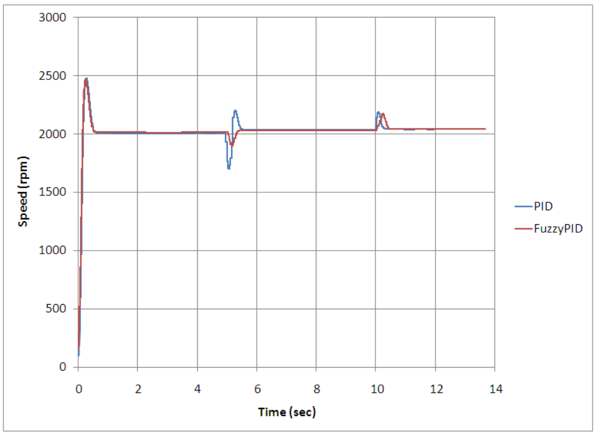
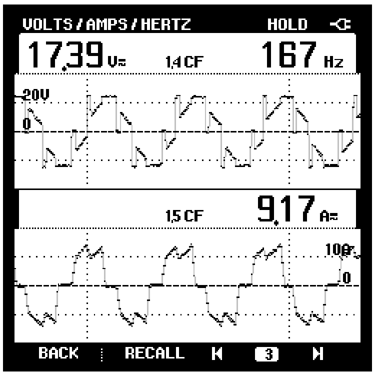
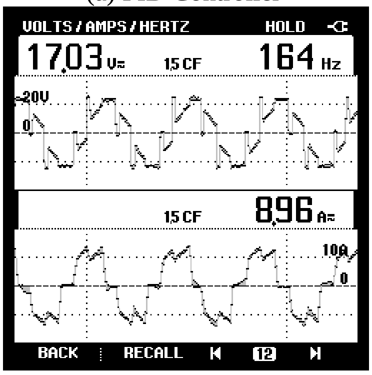


Fig. 14. Speed response to step load decrease at every 5s for PID and FuzzyPID controllers

As evident from Fig. 13 and Fig. 14, FuzzyPID controller yields better response during the transient of load increase and decrease with smaller overshoot and smaller settling time. It shows that the overshoot of the FuzzyPID controller is between 5% to 10% during the transient, while the PID controller exhibits up to 30% overshoot. Better robustness with respect to the load variation is one of the most frequently cited advantages of the Fuzzy Logic speed control over PID control. So the advantages of Fuzzy Logic can be adapted in the FuzzyPID controller which has been verified by the results in Fig. 13 and Fig. 14. However, during the steady-state motor operation, the motor terminal voltage waveforms and current waveforms do not show significant difference while the motor was under conventional PID controller and FuzzyPID controller respectively as shown in Fig. 15.



(a) PID Controller



(b) FuzzyPID Controller

Fig. 15. Motor terminal voltage voltage and current waveforms at 2000rpm speed and 3.8 Ω load

7. CONCLUSION

As observed from the simulation results, FuzzyPID controller shows a better performance compared to the PID controller since the former provides faster rise time, faster settling time and smaller overshoot. Hence, the proportional, integral and derivative gains in the FuzzyPID controller are dynamically and continuously tuned online for optimal motor performance.

From the experimental results, it can be concluded that FuzzyPID controller can tune the PID gains, via fuzzy algorithm in the source code embedded in PIC30F2010 microcontroller, online dynamically and continuously during motor operation. The most significant result is FuzzyPID controller managed to limit the overshooting during the step load changes in the experimental study up to 10% compared to PID controller. Therefore, the FuzzyPID controller is better equipped, more robust and more effective to handle load variations during motor operation. Moreover, the computing power of the PIC30F is so fast (40MHz clock freq), thus there is no apparent delay due to longer computation time in FuzzyPID controller. Whereas, the conventional PID controller has constant PID gains, optimally pretuned at specific motor speed. Therefore, as indicated by the simulation and experimental results, the FuzzyPID controller is better than conventional PID controller. The FuzzyPID controller provides very good speed response in all cases, consistent with reducing the rise time and settling time for all initial speed settings. Besides that, FuzzyPID controller is superior in reducing the overshoot of the speed response during the transient condition.

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