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SPEED CONTROL OF BLDC MOTOR WITH SEAMLESS SPEED REVERSAL CAPABILITY USING MODIFIED FUZZY GAIN SCHEDULING

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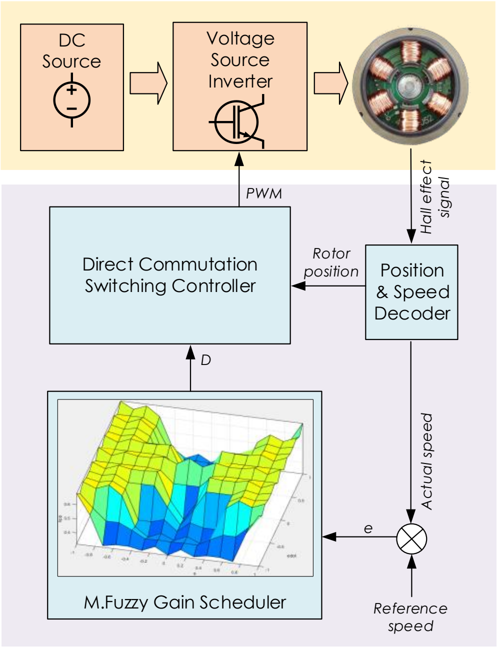
Graphical abstract



Abstract

Brushless Direct Current (BLDC) motors have gained popularity in recent years due to their high-power density. Many type of speed controller techniques have been developed and Proportional Integral Derivative (PID) controller has been the most widely used. However, PID's performance deteriorates during nonlinear loads conditions. Over the past five years, controllers have been developed to overcome this limitations in BLDC speed control, however the solutions are focusing on forward motoring only. In this paper, a speed controller for BLDC with seamless speed reversal using Modified Fuzzy Gain Scheduling is proposed. The proposed controller regulates the speed using Fuzzy Gain Scheduling 49 base rules. The controller was tested for six test cases and compared to PID and Self-Tuning Fuzzy PID controller. It is found out the proposed controller yields lowest steady state error, e_{ss} of 0.025 % during step-changing speed test case. Overall, Modified Fuzzy Gain Scheduling BLDC speed controller outperforms the other two similar controllers in variable speed conditions. The controller has potential to be used as bidirectional drive in highly dynamic load conditions.

Keywords: BLDC, Fuzzy Gain Scheduling, Bidirectional, Speed Controller, Matlab

Abstrak

Mutakhir ini motor arus terus tanpa berus (BLDC) telah mendapat perhatian komuniti system kawalan kerana prestasinya. Pelbagai jenis pengawal laju dihasilkan, Proportional Integral Derivative (PID) menjadi pilihan utama. Prestasi PID merosot ketika beban tidak linear. Pengawal laju lain telah dikembangkan untuk mengatasi had ini sejak lima tahun kebelakangan ini berfokus pada permotoran ke hadapan sahaja. Dalam kertas ini, Penjadualan Fuzzy Gain yang diubah suai untuk pengawal kelajuan BLDC dengan pembalikan arah yang lancar menggunakan comutasi secara berterusan adalah dicadangkan. Pengawal ini menggunakan 49 peraturan Penjadualan Fuzzy Gain. Pengawal ini telah diuji dengan enam kes ujian dan dibandingkan dengan pengawal laju PID dan Self-Tuning PID Fuzzy. Pengawal laju ini mempunyai steady state error, e_{ss} of 0.025 % yang rendah ketika ujian berubah laju. Keseluruhanya, pengawal kelajuan Fuzzy Gain Penjadualan yang diubah suai mengatasi prestasi pengawal laju yang lain ketika keadaan laju boleh ubah. Pengawal laju ini mempunyai pontensi untuk digunakan sebagai pemacu dwiarah ketika beban yang bersifat dinamik.

Kata kunci: BLDC, Fuzzy Gain Penjadualan, dwiarah, Pengawal Laju, Matlab

1.0 INTRODUCTION

Brushless Direct Current Motor (BLDC) has been a favourite motor in industry and transport due to high power density , efficiency and low maintenance cost [1-3]. A BLDC motor's rotor is made of permanent magnet and the number of pole pairs can vary from two to eight with alternate north (N) and south (S) poles. The motor uses electronic commutation where the stator winding is energized in a sequence to rotate it. Winding energization sequence is based on rotor position. Hence it is essential to know rotor position [4-5].

Three or more hall sensors are used to obtain the rotor position and speed measurement for a sensor-ed BLDC motor. The hall sensors coupled with trapezoidal or rectangular voltage drives the BLDC motor [6–9]. A closed loop speed controller required to ensure the motor operated at desired speed and direction.

Several speed controller techniques were developed to cater the BLDC motor operations through the years such as Proportional Integral derivative (PID) , Proportional Integral (PI), Proportional (P), and fuzzy based controllers [10-13].

PID controller is the most prominent due to its low cost and simple configuration compared to other types of controller such as fuzzy based or neuro-fuzzy controller [14-16]. However, PID controller's performance becomes reduced during nonlinear load and uncertainties in the system occurs [5,11].

To overcome PID controller's limitation, several types of intelligent control techniques using fuzzy has been developed [5,16-20].In [5], Rapid Control using Fuzzy for BLDC motor was developed. In [17], DC motor controller using Fuzzy-Neural Network was developed. In [18], an adaptive fuzzy logic was developed to control BLDC motor. Performance analysis of controllers for PI, ANFIS, fuzzy variable structure, and fuzzy tuned PID was conducted in [19]. In [20], Fuzzy Gain Scheduling of PID controller was developed for real time level control. Online trained neuro-fuzzy controller for BLDC motor was developed in [21]. In [5, 17-19, 21] the developed controllers were able to surpass the limitations of the PID controller however, the developed controllers are only for motor forwarding mode.

In [22], a controller using dsPIC for BLDC motor in four quadrant operation was tested. In [23], developed a controller using digital control strategy that is able to run in both forward and reverse motoring mode. However both authors [21-22], failed to provide sufficient data to suggest the controller able operate in reverse motoring mode. Furthermore in [24], the position information error during reversal motoring mode has twice of the phase lag angle compared to forward motoring mode was proved. Therefore the controller must be able to determine the ideal positions of the rotor for reversal [6, 21-22, 24].

In this paper, speed control of BLDC motor with seamless speed reversal capability using modified fuzzy gain scheduling was proposed. Based on the direction and speed the controller will use the fuzzy gain scheduling base rules to meet the requirements. The systems were designed and tested using Matlab Simulink. This controller tested for several test cases along with PID and Self-Tuning Fuzzy PID controller.

2.0 METHODOLOGY

BLDC Motor's Speed control is as represented in Figure 1. The mathematical equation of BLDC motor can be expressed by the following matrix was derived by the author [19]:

$$\begin{bmatrix} L_a & M_{ab} & M_{ac} \\ M_{ba} & L_b & M_{bc} \\ M_{ca} & M_{cb} & L_c \end{bmatrix} \frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

where the phase voltages of the BLDC motor are represented by V_a, V_b and V_c. The stator winding resistance are represented by R_a, R_b and R_c while the i_a, i_b and i_c are the phase current of the motor. L_a, L_b and L_c are the motor's self-inductance and M_{ab}, M_{ac}, M_{ba}, M_{bc}, M_{ca} and M_{cb} are the mutual inductances between stator windings. The electromechanical torque can be derived as:

$$T_{em} = J\frac{d\omega_r}{dt} + \beta\omega_r + T_L \quad (2)$$

where J is the inertia of the rotor (kgm^2), ω_r is the motor's angular velocity and B denotes frictional constant. Mechanical load (Nm) is represented by T_L. In order to determine the electromagnetic torque of a 3-phase BLDC motor, the speed, current and back-EMF waveforms are required. Hence, the instantaneous electromagnetic torque equation could be rearranged and typified as following:

$$T_{em} = \frac{1}{\omega_m}(e_a i_a + e_b i_b + e_c i_c) \quad (3)$$

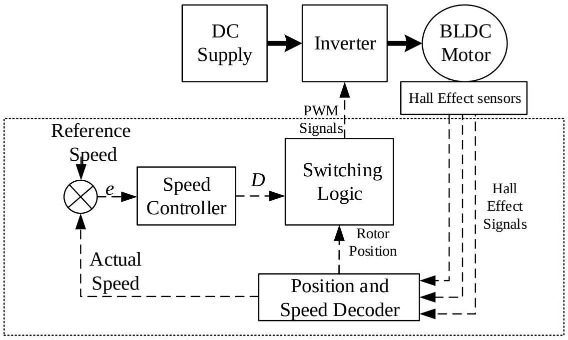


Figure 1 Speed Control of BLDC Motor

Fuzzy Gain Scheduler proposed by [26] was tested and the results were unsatisfying as it takes 1.17 ms longer to achieve the desired speed during no load conditions compared to conventional PID controller as the values of Proportional Gain (Kp), Integral Gain (K*i*) and Derivative Gain (K*d*) that fed to the PID controller increases slowly and determined by the error. To overcome this problem, a Modified Fuzzy Gain Scheduler was proposed to achieve faster responds as shown in Figure 2.

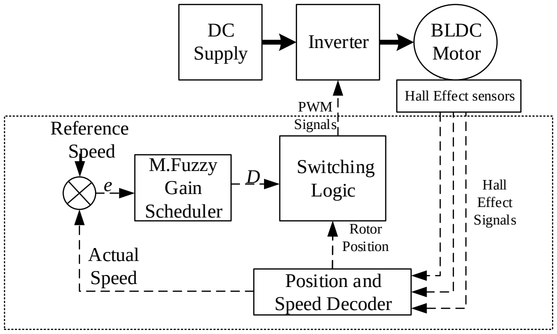


Figure 2 Proposed Controller

PID controller's mathematical equivalent can be expressed as following equation:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{\partial e(t)}{\partial t} \qquad (4)$$

where Kp, Ki and Kd are the proportional, integral and derivative gain coefficient. This parameter could be modified further to obtain the best response based on the requirement. By including the fuzzy logic, the Kp and Kd become a ranged gain. The suitable values are determined by the fuzzy rules. For conveniences Kp and Kd are simplified using the following formulas:

$$Kp = (Kpmax - Kpmin)K'p - Kpmin \qquad (5)$$

$$Kd = (Kdmax - Kpmin)K'd - Kdmin \qquad (6)$$

where *Kpmax* and *Kdmax* are the highest pervious coefficient gain while the *Kpmin* and *Kdmin* are the smallest pervious coefficient gain. *K'p* and *K'd* are the fuzzy membership function. By using the current error *e(k)* and rate of error Δ*e(k)*, PID parameters were determined. The following equation is used to determine the integral time constant:

$$Ti = \alpha Td \qquad (7)$$

and the integral gain obtain by using the equation:

$$Ki = \frac{Kp}{\alpha Td} = Kp^2/(\alpha Kd) \qquad (8)$$

where the alpha (α) is the ratio of integral constant. Internal structure of the proposed fuzzy uses current error *e(k)* and rate of error Δ*e(k) as inputs and has three outputs. The three outputs are K'p, K'd* and alpha (α). The degree of membership for both current error *e(k)* and rate of error Δ*e(k)* as depicted by Figure 3, where Zero (ZO), Negative Big (NB), Positive Big (PB), Negative Medium (NM), Positive Medium (PM), Negative Small (NS), and Positive Small (PS). The degree of membership for *K'p* and *K'd* shown in Figure 4 while the degree of membership for alpha (α) is represented by Figure 5.

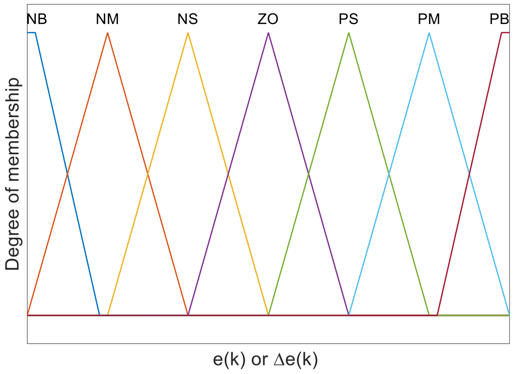


Figure 3 Degree of membership of e(k) and Δe(k)

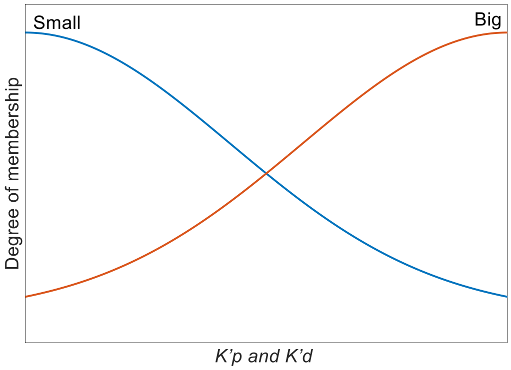


Figure 4 : Degree of membership for K'p and K'd

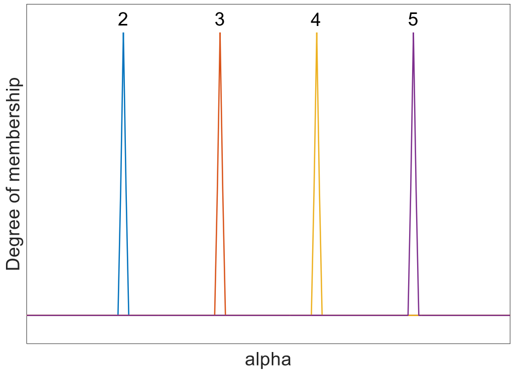


Figure 5 : Degree of membership for alpha

Based on the membership functions rules table were used to obtain 49 set of rules. Table 1, 2 and 3 are the rules table for *K'p*, *K'd* and alpha respectively.

Table 1 Fuzzy Rules for *K'p*

					Δ***e*(*k*)**			
		NB	NM	NS	ZO	PS	PM	PB
***e*(*k*)**	NB	B	B	B	B	B	B	B
	NM	S	B	B	B	B	B	S
	NS	S	S	B	B	B	S	S
	ZO	S	S	S	B	S	S	S
	PS	S	S	B	B	B	S	S
	PM	S	B	B	B	B	B	S
	PB	B	B	B	B	B	B	B

Table 2 Fuzzy Rules for *K'd*

					Δ***e*(*k*)**			
		NB	NM	NS	ZO	PS	PM	PB
***e*(*k*)**	NB	S	S	S	S	S	S	S
	NM	B	S	S	S	S	S	B
	NS	B	B	S	S	S	B	B
	ZO	B	B	B	S	B	B	B
	PS	B	B	S	S	S	B	B
	PM	B	S	S	S	S	S	B
	PB	S	S	S	S	S	S	S

Table 3 Fuzzy Rules for Alpha

					Δ***e*(*k*)**			
		NB	NM	NS	ZO	PS	PM	PB
***e*(*k*)**	NB	2	2	2	2	2	2	2
	NM	3	3	2	2	2	3	3
	NS	4	3	3	2	3	3	4
	ZO	5	4	3	3	3	4	5
	PS	4	3	3	2	3	3	4
	PM	3	3	2	2	2	3	3
	PB	2	2	2	2	2	2	2

Figure 6 shows the types of controllers used in this study. Figure 6 (a) shows Proportional Integral Derivative Controller. The PID controller was tuned using Ziegler-Nichols (ZN) method. Self-Tuning Fuzzy PID controller designated by Figure 6 (b). The design was based on Heuristic method. A large number of rules were required to ensure desirable results. Figure 6 (c) shows the proposed controller in this study. All the speed controllers will be using Direct Commutation Switching scheme controller as shown in Figure 7. The switching controller uses complex mathematical switching scheme based on clockwise (CW) and counter clockwise (CCW) commutation sequence for BLDC motor as shown in Table 4 and 5 to control the speed and direction of the BLDC motor.

By utilizing the duty cycle, rotor position and motor rotation direction, the direct switching scheme controller calculates the sequence and timing for the commutation. Hence, producing the PWM for the inverter.

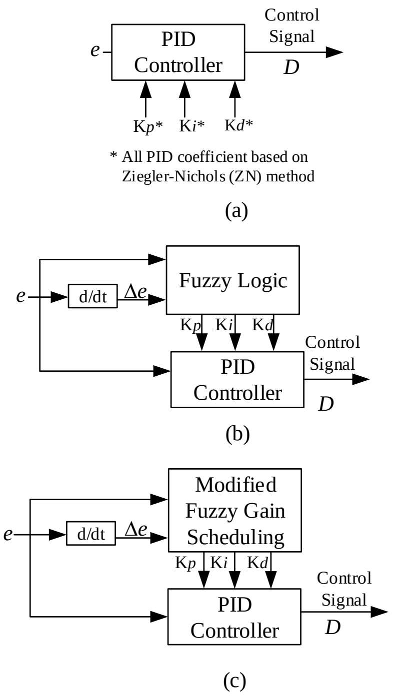


Figure 6 Types of Speed Controller used

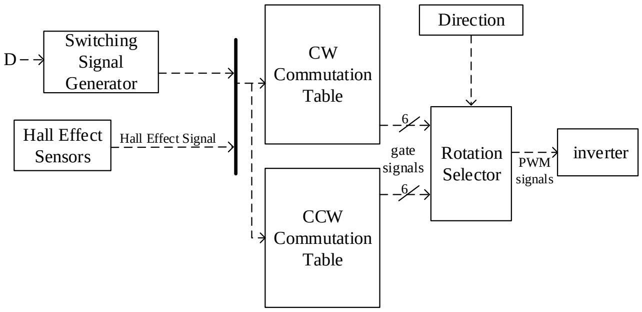


Figure 7 Direct commutation switching scheme controller

Table 4 BLDC Commutation sequence for clockwise (CW) direction

Sequence	Hall Sensor Input			Back EMF Phase Current		
	A	***B***	***C***	***a***	***b***	***c***
1	0	1	1	I+	I-	0
2	0	0	1	I+	0	I -
3	1	0	1	0	I+	I -
4	1	0	0	I -	I +	0
5	1	1	0	I -	0	I +
6	0	1	0	0	I -	I +

Table 5 BLDC Commutation sequence for counterclockwise (CCW) direction

Sequence	Hall Sensor Input			Back EMF Phase Current		
	A	***B***	***C***	***a***	***b***	***c***
1	0	1	1	0	I -	I +
2	0	0	1	I -	0	I +
3	1	0	1	I -	I +	0
4	1	0	0	0	I +	I -
5	1	1	0	I +	0	I -
6	0	1	0	I +	I -	0

3.0 RESULTS AND DISCUSSION

The proposed controller is tested with a system design using Simulink as shown in Figure 2. In the Simulink model, a BLDC motor with specification as shown in Table 6 was used. The controller was tested for six test cases; (1) constant speed during no load condition, (2) constant speed during full load condition, (3) constant speed with speed during no load to full load condition, (4) constant speed with speed during full load to half load condition, (5) step-changing speed during full load conditions, (6) varying direction during full load conditions. The results of Steady State Error (ess), Rise time (Tr), overshoot (Mp), and Settling time (Ts) were compared to ZN-Tuned PID Controller and Self-Tuning Fuzzy PID controller under the same test cases.

Table 6 Specifications of BLDC Motor

Specifications	Value
Rated voltage (V)	500
Rated current (A)	2.23
Rated speed (rpm)	1500
Stator phase resistance R (Ω)	3
Stator phase inductance L (H)	0.001
Flux linkage established by magnets (V s)	0.175
Voltage constant (V/rpm)	0.1466
Torque constant (N m/A)	1.4
Moment of inertia (kg m2/rad)	0.0008
Friction factor (N m/(rad/s))	0.001
Pole pairs	4

3.1 Response of the Motor for Constant Speed During No Load

For both clockwise (CW) and counter clockwise (CCW) direction, the speed was set at 1500 rpm with no load. The results are depicted by Figure 8 for CW direction and Figure 9 for CCW direction respectively. Figure 10 and Figure 11 shows the BLDC motor phase currents during no load conditions for the different directions. The BLDC motor response was tabulated in Table 7 and 8. It could be observed that during both directions the Self-Tuning Fuzzy PID and Modified Fuzzy Gain Scheduling controller has overshoot while the ZN-Tuned PID controller does not have overshoot. The rise time for Self-Tuning Fuzzy PID is the fastest at 3.6 ms but the Modified Fuzzy Gain Scheduling controller has the fastest settling time during both directions. It is observed that, a delay of 0.2 ms during CCW direction for Self-Tuning Fuzzy PID controller. The ZN-Tuned PID has the worse steady state error, settling time and rise time despite not having any overshoot.

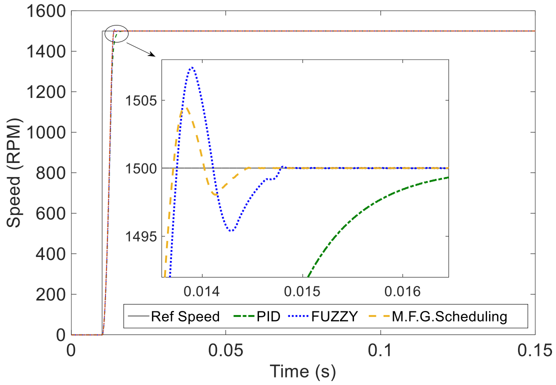


Figure 8 Motor Speed Response During No Load for CW Direction

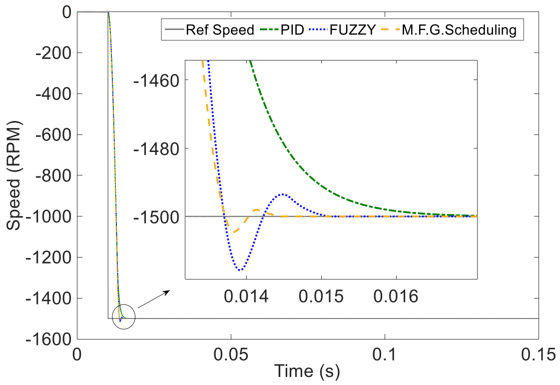


Figure 9 Motor Speed Response During No Load for CCW Direction

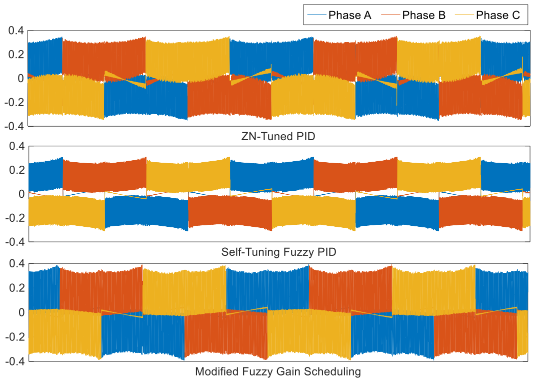


Figure 10 Phase currents of BLDC motor During No Load for CW direction

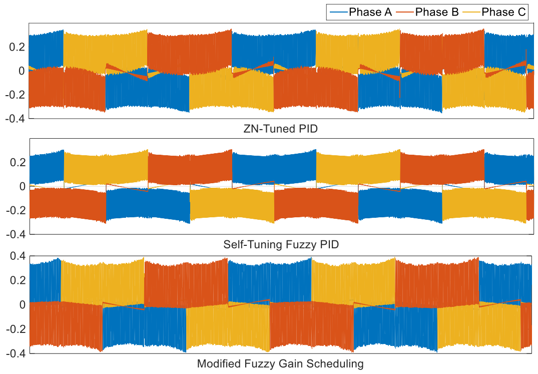


Figure 11 Phase currents of BLDC motor During No Load for CCW direction

Table 7 Motor Response during CW for No Load

Techniques	M_p (%)	T_r (ms)	T_s (ms)	e_{ss} (%)
ZN-Tuned PID	-	7.70	7.70	0.00123
Self-Tuning Fuzzy PID	1.26800	3.60	5.40	0.00093
Modified Fuzzy Gain Scheduling	0.30000	3.70	4.50	0.00067

Table 8 Motor Response during CCW for No Load

Techniques	M_p (%)	T_r (ms)	T_s (ms)	e_{ss} (%)
ZN-Tuned PID	-	7.70	7.70	0.00123
Self-Tuning Fuzzy PID	1.85500	3.60	5.60	0.00097
Modified Fuzzy Gain Scheduling	0.30000	3.70	4.50	0.00067

3.2 Response of the Motor for Constant Speed During Full Load

The response for the motor for CW and CCW are depicted by Figure 12 and Figure 13 respectively for full load of 3 Nm. Figure 14 and Figure 15 shows the BLDC motor phase currents during full load conditions for the different directions. The response data is tabulated in Table 9 and Table 10 respectively. For both CW and CCW direction only Self-Tuning Fuzzy PID has the shortest rise time of 3.8 ms but it is the only one has overshoot of 0.50627 % for CW and 0.98373 % CCW directions. The rise time for both directions for Modified Fuzzy Gain Scheduling remained same and consistent at 4.0 ms however its steady state error is much higher than ZN-Tuned PID. Overall Modified Fuzzy Gain Scheduling performed better than other controllers.

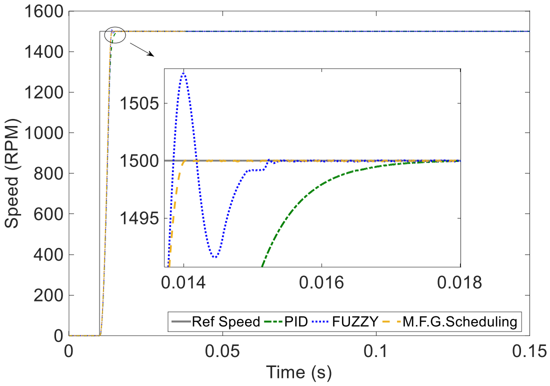


Figure 12 Motor Speed Response During Full Load for CW Direction

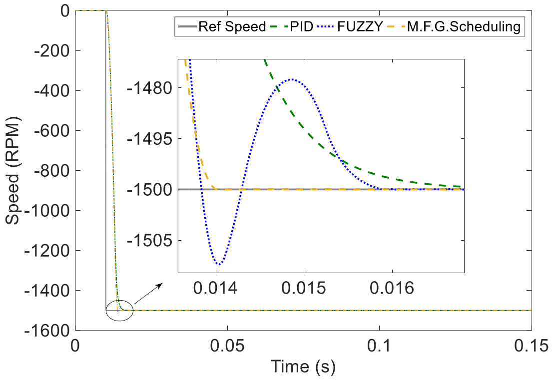


Figure 13 Motor Speed Response During Full Load for CCW Direction

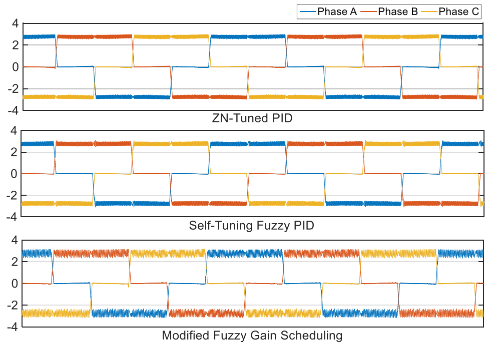


Figure 14 Phase currents of BLDC motor During Full Load CW direction

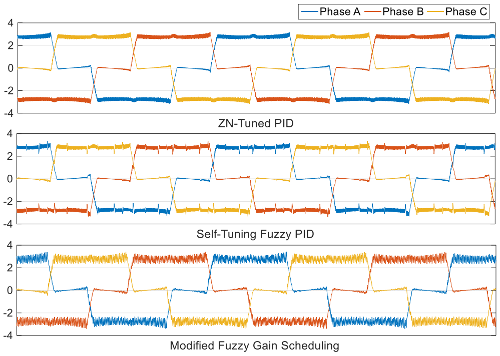


Figure 15 Phase currents of BLDC motor During Full Load CCW direction

Table 9 Motor Response during CW for Full Load

Techniques	M_p (%)	T_r (ms)	T_s (ms)	e_{ss} (%)
ZN-Tuned PID	-	8.50	8.50	0.01041
Self-Tuning Fuzzy PID	0.50627	3.80	5.50	0.01960
Modified Fuzzy Gain Scheduling	-	4.00	4.00	0.01130

Table 10 Motor Response during CCW for Full Load

Techniques	M_p (%)	T_r (ms)	T_s (ms)	e_{ss} (%)
ZN-Tuned PID	-	8.30	8.50	0.01040
Self-Tuning Fuzzy PID	0.98373	3.80	5.90	0.00704
Modified Fuzzy Gain Scheduling	-	4.00	4.00	0.01140

3.3 Response of the Motor for Constant Speed During No Load to Full Load Condition

The feedback of the motor during load change from 0 Nm to 3 Nm at t = 0.05 s is represented by Figure 16 and the data is tabulated in Table 11. The recovery time for both Self-Tuning Fuzzy PID and Modified Fuzzy Gain Scheduling is the same at 0.8 ms which is better compared to ZN-Tuned PID. Overall the Modified Fuzzy Gain Scheduling did better than other controllers despite having higher steady state error during no load and full load conditions.

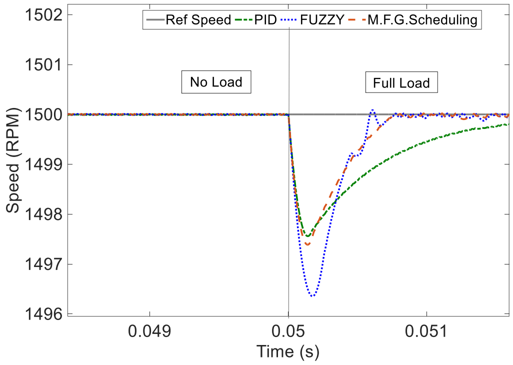


Figure 16 Motor Speed Response During No Load to Full Load for CW Direction

Table 11 Motor Response During No Load to Full Load

Techniques	Recovery Time (ms)	Before Load Change e_{ss} (%)	After Load Change e_{ss} (%)
ZN-Tuned PID	2.50	0.00123	0.00500
Self-Tuning Fuzzy PID	0.80	0.00093	0.01237
Modified Fuzzy Gain Scheduling	0.80	0.00067	0.01130

3.4 Response of the Motor for Constant Speed During Full Load to Half Load Condition

The load was changed from full load 3 Nm to 1.5 Nm at t = 0.05 s. The motor speed response is shown in Figure 17 and the data is tabulated in Table 12. The recovery time of the ZN-Tuned PID is the worse at 1.8 ms while the other controllers has the same time of 0.3 ms. Despite the late recovery the ZN-Tuned PID has the lowest steady state error.

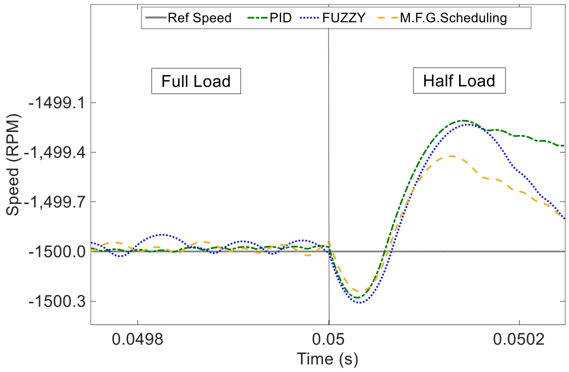


Figure 17 Motor Speed Response During Full Load to Half Load for CCW Direction

Table 12 Motor Response During Full Load to Half Load

Techniques	Recovery Time (ms)	Before Load Change e_{ss} (%)	After Load Change e_{ss} (%)
ZN-Tuned PID	1.8	0.01040	0.00120
Self-Tuning Fuzzy PID	0.3	0.00704	0.00567
Modified Fuzzy Gain Scheduling	0.3	0.01140	0.00410

3.5 Response of the Motor for Step-changing Speed During Full Load

The response for the step-changing speed during full load of 3 Nm at t = 0.05 s represented by Figure 18 and the data is tabulated in Table 13. There was no overshoot observed during speed change from 1500 rpm to 2000 rpm. During this time, the Self-Tuning Fuzzy PID performed better compared to the other controller as it has the best rise time at 3.40 ms during speed change from 1500 to 2000 rpm. However, the ZN-Tuned PID's steady state error has increased during the speed change. Both Self-Tuning Fuzzy PID and Modified Fuzzy Gain Scheduling's steady state error has decreased.

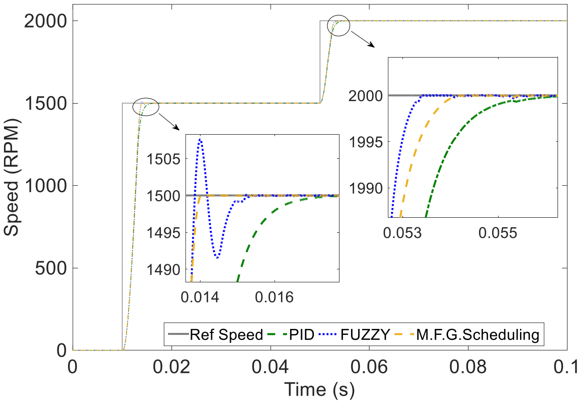


Figure 18 Motor Speed Response During Full Load for CW Direction

Table 13 Motor response for the step-changing speed

Techniques	Step change T_r (ms)	Step change T_s (ms)	Before Speed Change e_{ss} (%)	After Speed Change e_{ss} (%)
ZN-Tuned PID	6.7	6.9	0.01040	0.01350
Self-Tuning Fuzzy PID	3.4	3.5	0.01960	0.06900
Modified Fuzzy Gain Scheduling	4.1	4.1	0.0113	0.00320

3.6 Response of the Motor for Varying Direction During Full Load

Figure 19 shows the results of the BLDC motor speed for different controllers for varying direction for full load conditions. It can be observed that all controllers undertest are able to cater for the direction changes from CCW to CW. However, during direction change, the Self-Tuning Fuzzy PID has overshoot of 0.06371 % despite not having any overshoot during step-changing speed as shown in Figure 18. The Modified Fuzzy Gain Scheduling has the fastest settling time of 7.3 ms. The ZN-Tuned PID's steady state error during CW is the smallest compared to other controllers. The Table 14 shows the motor feedback during this study case

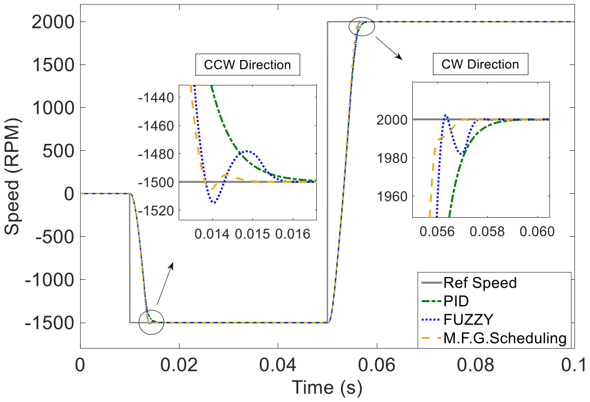


Figure 19 Motor Speed Response During Full Load for both CW and CCW Direction

Table 14 Motor response for varying directions

Techniques	CW T_r (ms)	CW T_s (ms)	CCW e_{ss} (%)	CW e_{ss} (%)
ZN-Tuned PID	9.7	9.7	0.01040	0.0054
Self-Tuning Fuzzy PID	6.5	7.8	0.00704	0.064
Modified Fuzzy Gain Scheduling	7.3	7.3	0.0114	0.025

It can be concluded that for all the test cases under study the proposed controllers performed better compared to other controllers under test. However, the steady state error of the proposed controller is slightly higher compared to its counterparts, although still within acceptable region. This is expected as the controller sacrifices its stability for better dynamic performance.

4.0 CONCLUSION

In this study, a Speed Control of Bldc Motor with Seamless Speed Reversal Capability using Modified Fuzzy Gain Scheduling was proposed. The proposed controller able to perform valiantly for all the test cases. However, there is some limitation to the controller during load changes from no load to full load conditions. The steady state error of the proposed controller is higher compared to its counterparts but the error is within acceptable region. Hence this controller can be used to drive a BLDC motor bidirectional for real time applications.

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