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Procedia Computer Science 132 (2018) 623–631

Procedia Computer Science

www.elsevier.com/locate/procedia

International Conference on Computational Intelligence and Data Science (ICCIDS 2018)

Performance Review of Fuzzy Logic Based Controllers Employed in Brushless DC Motor

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Abstract

The paper presents a performance review of Fuzzy Logic Control technique when applied to Brushless DC motor (BLDC). These type of motors are non-linear in nature therefore classical PID control scheme fail to achieve desired steady state performance. To achieve the control objective, Fuzzy Logic Control scheme in arrangement with various other control techniques were investigated by several researcher. These techniques differ in various aspect such as control architecture, controller tuning method, dynamic and steady state performance. The paper presents a comprehensive performance review of such Fuzzy Logic Based Controllers.

Peer-review under responsibility of the scientific committee of the International Conference on Computational Intelligence and Data Science (ICCIDS 2018).

Keywords: Brushless DC Motor; Fuzzy Logic Controller; PID; Steady state performance;

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Peer-review under responsibility of the scientific committee of the International Conference on Computational Intelligence and Data Science (ICCIDS 2018).
10.1016/j.procs.2018.05.061

1. Introduction

Brushless DC motors are characterized by higher efficiency, reliability and wide speed range. Due to such individualities BLDC motor is very common in various industrial and consumer durables, the biomedical and robotic application [1] requires high torque to weight ration and precise position control for accuracy. Therefore BLDC motor may be considered to be a suitable choice [2] as compared to its AC and DC counterparts but the barrier is electronic commutation in BLDC motor which contributes torque ripple [3] due to inaccurate installation of position sensors. A BLDC motor is electronically commutated in place of mechanical commutation based on rotor position feedback. This feedback can be either sensor based or sensor less. Position sensors as feedback element are prone to physical parameter variation i.e. temperature, pressure, humidity etc. therefore sensor-less rotor position detection [3][4] has received more and more focus. The sensor-less method mainly include the back EMF based method, Flux Linkage based method, the inductance based method, and the artificial intelligence based method.

Proportional Integral and Derivative (PID) based control scheme is predominantly being used in the industry due to inherent advantage of simple structure and robust operation [5]. Even in today's scenario, more than 95% of closed loop industrial controllers are PI or PID based [6] but this controller is not considered suitable for BLDC motor because of nonlinear behavior of the later. To cater for the nonlinear parameter variation of BLDC motor, various artificial intelligence based methods were proposed by researcher. Out of these controllers, Fuzzy Logic based control structure has been presented at number of occasion

Nomenclature

PID	proportional integral and derivative control action
PI	proportional and integral control action
FLC	fuzzy logic controller
EKF	extended kalman filter
PSO	particle swarm optimization
GA	genetic algorithm
ANFIS	adaptive neuro - fuzzy inference system
BLDC	brushless direct current motor
RPM	reference speed in revolution per minutes
Ref. No.	serial no of the reference cited
NR	not reported parameter
NL	no load condition of motor
L	loaded condition motor
V_a	phase voltage of phase a
V_b	phase voltage of phase b
V_c	phase voltage of phase c
i_a	phase current of phase a
i_b	phase current of phase b
i_c	phase current of phase c
e_a	back emf of phase a
e_b	back emf of phase b
e_c	back emf of phase c
L	armature self-inductance in H
R	armature reaction in Ohm
J	inertia
B	friction co-efficient
T	torque
t_r	rise time
t_s	settling time
M_p	maximum overshoot

e_{ss}	steady state error

2. Mathematical modelling of BLDC motor

The modelling of BLDC motor can be compared to that of three phase synchronous motor [7]. The fundamental equation governing the armature voltage equation of BLDC motor [3] can be represented by following mathematical equation.

$$V_a = L\frac{dI_a}{dt} + R.I_a + e_a \tag{1}$$

$$V_b = L\frac{dI_b}{dt} + R.I_b + e_b \tag{2}$$

$$V_c = L\frac{dI_c}{dt} + R.I_c + e_c \tag{3}$$

Equation 1 through 3 can be rewritten in following form

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_a & L_{ab} & L_{ac} \\ L_{ba} & L_b & L_{bc} \\ L_{ca} & L_{cb} & L_c \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{4}$$

In above equation if we assume that windings are not saturated, iron loss is negligible, phase winding resistances are equal, zero mutual inductance between phase winding and constant self- inductance then it reduces to.

$$L_a = L_b = L_c = L \tag{5}$$

$$L_{ba} = L_{bc} = L_{ca} = \mathbf{M} = 0 \tag{6}$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + Lp\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} + \begin{bmatrix} V_n \\ V_n \\ V_n \end{bmatrix} \tag{7}$$

The Back EMF of non-conducting phase is given by

$$e_a = K_e f(\theta_e) W_r \tag{8}$$

$$e_b = K_e f\left(\theta_e - \frac{2\pi}{3}\right) W_r \tag{9}$$

$$e_c = K_e f\left(\theta_e + \frac{2\pi}{3}\right) W_r \tag{10}$$

The torque equation is as follows.

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{W_r} \tag{11}$$

$$T_e = T_L + J\frac{dw}{dt} + Bw \tag{12}$$

$$T_e = K_t I \tag{13}$$

The output power is given by

$$P = T_e W_r \tag{14}$$

Therefore the speed response of BLDC motor is dependent on parameters R, B and J. Schematic diagram of three phase BLDC motor is depicted in figure 1.

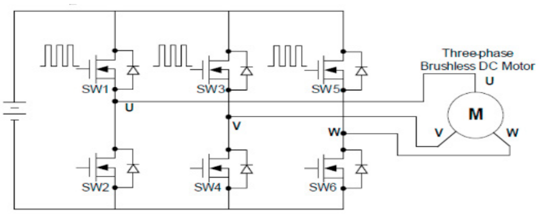

Fig 1. Schematic diagram of three Phase BLDC Motor.

3. Fuzzy Logic Controller

Fuzzy logic controller (FLC) has demonstrated its capability to handle plant nonlinearity without the requirement of its mathematical model [8][9]. This controller is being used in various industrial application as well [10], [11]. General configuration of FLC consist of following four stages namely.

- Fuzzification.
- Knowledge base.
- Fuzzy inference.
- De-Fuzzification.

These stages are depicted in figure. 2.

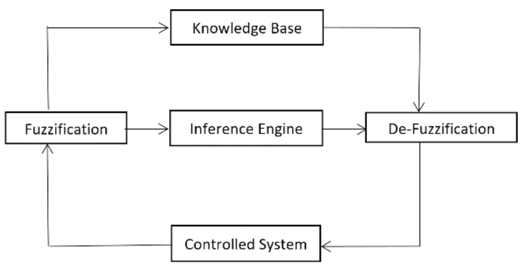

Fig 2. Schematic diagram of fuzzy logic controller.

During the Fuzzification stage the input plant parameters are converted into linguistic fuzzy variable. Second part Knowledge base also known as expert knowledge provides the necessary database to frame the linguistic control rules. The linguistic rule base describes the control goal and control policy. This part provides linguistic control rules based on expert knowledge database. The third part Inference Engine is the brain of Fuzzy Logic Controller where the decision making and logical reasoning similar to human type decision making is simulated based on fuzzy perception, fuzzy inference control rules and fuzzy implication. The fourth part De-Fuzzification performs the task of scale mapping of the range of values of output variables into corresponding universe of discourse to yield a non-fuzzy control action based on inferred fuzzy control rule. This transformation is performed using fuzzy membership function. The number of membership function and their shapes are determined by user at initial stage only.

3.1. Performance analysis of Fuzzy logic Controlled BLDC motor.

Fuzzy based controllers has been offered by several researcher to cater for nonlinearity in BLDC motor and to achieve reduced starting current, rising time and speed overshoot [12]. Application of FLC based BLDC motor controller was successfully demonstrated in [13] another application yielded smaller torque ripple at low speed [14]. Speed response of the fuzzy logic controller presented by various researcher when applied to BLDC motor is gathered and presented in Table. 1

Table 1. Performance comparison of Fuzzy Logic Controlled BLDC motor

Ref.	Year	Ref. Speed	PI Controller				FLC Controller			
No.		(RPM)	t_r	t_s	M_p	e_{ss}	t_r	t_s	M_p	e_{ss}
[15]	2014	400	NR	0.02	6.667	NR	NR	0.03	00	00
[16]	2013	1500	0.4	1.0	13	3.5	0.08	0.1	0.17	3.5
[17]	2013	500	NR	6.7	4.9	4	NR	4.2	00	22
		1000	NR	9.0	1.54	9	NR	4.3	00	27
[18]	2012	1000	NR	19.2	45	NR	NR	14.09	38	NR
		2000	NR	19.67	20.15	NR	NR	14.06	17.05	NR
		3000	NR	19.76	6.07	NR	NR	14.1	4.77	NR
		4000	NR	20.58	1.93	NR	NR	15	0.77	NR

PI controller exhibited high speed drop under load condition and FLC was able to display a comparatively [19] faster response then PI controller further FLC was able to reduce the starting current and torque ripple at the cost of reduced starting torque [20]. It has been observed that FLC was able to improve the dynamic performance but with certain limitation as well, not only this only few literatures were not able to report the crucial dynamic response parameter rise time [15][17][18] and steady state error [18] of reported control scheme . To overcome such limitation FLC is combined with other control techniques.

4. Fuzzy PI/PID Controller

BLDC motor suffers from cogging torque and the load disturbance [8] and Fuzzy Logic Controller alone resulted in reduced starting torque. Even increase in steady state error was also reported[17]. To overcome the controller limitation, efforts has been made by various researcher to combine the FLC with PI/PID controller for application into electric vehicle [8], Dynamic Electric Vehicle [21], and Electro-Mechanical Actuator [5]. A Fuzzy controllers design process is not yet standardized [22] still it provides good start up speed response and PI controllers response over load torque variation was found to be very impressive but later one has relatively slow settling time [23]. Hybrid controller has integrated the advantage of both control structures. Dynamic response of combination of Fuzzy and PI/PID controllers reported in various literature are arranged in table.2.

Table2. Performance comparison of Fuzzy PI/PID Controlled BLDC motor

Ref. No.	Year	(RPM)	PI/PID Controller t_r	t_s	M_p	e_{ss}	PI/PID-FLC Controller t_r	t_s	M_p	e_{ss}
[21]	2017	100	34.48	NR	-1.75	NR	66	0.233	9.783	NR
		700	35.37	NR	-1.74	NR	68	0.235	7.447	NR
[24]	2017	1000	20	12.2	NR	90	19	09	00	00
		4000	22	22.5	NR	70	21	11.8	00	00
[25]	2015	NR	0.0091	0.053	12.1	NR	0.002	0.015	6.6	NR
[26]	2014	3000 to 2000 NL	0.0602	0.32	2.8	NR	0.036	0.034	0.07	NR
		3000 to 2000 L	0.011	0.543	2.5	NR	0.033	0.021	0.03	NR
[27]	2013	3000	0.04	0.133	169	NR	0.039	0.119	163.5	NR
[8]	2012	200	NR	NR	NR	NR	0.01	NR	00	00
		400	NR	NR	NR	NR	0.1	NR	00	00
[9]	2012	1500	0.025	0.61	38.66	NR	0.020	0.51	37.00	NR
		3000	0.030	0.7	22.66	NR	0.035	0.60	21.54	NR
[28]	2012	3500	NR	0.0053	2.5	14	NR	0.004	0.2	0.5
[29]	2012	3500	0.021	0.40	15.71	NR	0.052	0.25	0.42	NR
		1000 to 1500 NL	0.020	0.35	16.40	NR	0.004	0.15	55.10	NR
		1000 to 1500 L	0.020	0.35	15.40	NR	0.005	0.15	40.30	NR
[30]	2011	3500 L	0.0210	0.40	15.71	NR	0.052	0.25	0.42	NR
		1000 to 15000NL	0.0201	0.35	16.4	NR	0.0042	0.15	55.10	NR
		1000 to 15000NL	0.0209	0.35	15.4	NR	0.0051	0.15	40.30	NR
		3500 to 3000 L	0.0210	0.35	15.71	NR	0.0522	0.25	0.42	NR

As compared to classical PID/PI controller and Fuzzy controller, Fuzzy based PI/PID controller exhibited the reduced rise time, settling time and speed fluctuation on MATLAB simulation [31][1][32][33] and its physical implementation [24][34][35][36][37]. However, during the course of review it has also been observed that performance of Fuzzy PID controller is not always superior to PID controller in every aspect. It has been witnessed that the Fuzzy PID lead to substantial increase in rise time [29][9][21][26][30] and maximum overshoot [29][21][30] at various occasions. Therefore Fuzzy based PI/PID controller is not able to establish its superiority in every aspect.

5. Various other Fuzzy based Control scheme

Tuning process of fuzzy PI structure is a complex task and it dependent on various input variables along with no of rule base [22] and Fuzzy PID controller did exhibited unreliable rise time and maximum overshoot at some occasion. Therefore various other control scheme was combined with Fuzzy logic controller and was presented by researcher to control the BLDC motor drive. Some of these scheme are presented in table 3.

Table 3. Fuzzy based Control schemes for BLDC motor

Ref. No.	Year	Control Structure	Brief Description of the Control Scheme.
[38]	2017	Fuzzy Sliding Mode Controller	Constant of Sliding Mode Control law is varied by Fuzzy Logic Controller
[39]	2017	Particle Swarm Optimized Fuzzy Logic Controller	Torque control of BLDC motor based on PSO and Fuzzy Logic controller.
[40]	2017	Whole Fuzzy Controller	Fuzzy controller based on continuity intelligent weight function not on membership function and control rule
[41]	2016	Interval Type-2 Fuzzy Logic Controller	Type-2 Fuzzy allows to model the effects of uncertainty in the rule based fuzzy system.
[42]	2016	Hybrid Fuzzy Sliding Mode Controller	Fuzzy consolidated sliding mode controller with moving weight condition.
[43]	2016	Improved variable universe Fuzzy PID	PSO based scale factor parameters in offline optimization for reduced tuning time
[44]	2014	Compensated Fuzzy Neural Network controller	Hybrid System Combining Advantage of Compensation Logic and Neural Network
[45]	2013	PID Sliding Mode Fuzzy Controller	PID tuning by Sliding mode fuzzy for chattering elimination & improved response
[46]	2012	Hybrid PI controller	Fuzzy pre-compensator is used to modify controller to compensate output variation
[47]	2011	Extended Kalman Filter (EKF) - Fuzzy-Neural –Network Controller	EKF filters the noise in the error and delta error and prevents controller to process noise at cost of delayed response
[48]	2011	Sliding Mode Control and fuzzy control scheme.	Control efforts proportional to distance from sliding surface for chattering dismissal
[49]	2008	Parallel Fuzzy PID Controller	Three parallel Fuzzy sub-controller that update the value of PID gains online
[50]	2005	Emotional learning based Neuro-Fuzzy Controller	Supervisory learning algorithm (as Critic) controls the network behavior
[51]	2004	Genetic Algorithm (GA) based Fuzzy Controller	GA based optimization and Online tuning of fuzzy parameters for robust performance.
[52]	2001	Adaptive Neuro - Fuzzy Inference System (ANFIS)	Neuro structured learning algorithm find appropriate fuzzy logic rule, then parameter learning algorithm to fine tune membership function and other parameters

6. Conclusion

Performance review of Fuzzy logic based control scheme is presented in this paper. During the study it was observed that, although fuzzy logic controller displayed improvement in dynamic performance of BLDC motor operating parameters but still it could not establish its superiority indisputably in terms of steady state performance at times. Various different control scheme were also combined with Fuzzy controller to further improve upon its limitation but further efforts are still need of the hour.

7. References

[1] P. H. Yang Sheng, Xingcheng Wang, Longda Wang. (2017) "Fuzzy PID Control Syatem Design of Brushless DC Motor Based on Vector Control," Chinese Automation Congress: 5583–5587.

[2] Q. Chen, G. Liu, W. Zhao, L. Qu, and G. Xu. (2017) "Asymmetrical SVPWM Fault-Tolerant Control of Five-Phase PM Brushless Motors," IEEE Trans. Energy Convers., 32(1): 12–22.

[3] J. Sriram and K. Sureshkumar (2014) "Speed Control of BLDC Motor Using Fuzzy Logic Controller Based on Sensorless Technique," International Conference on Green Computing Communication and Electrical Engineering: 1–6.

[4] J. S. Rao and D. O. C. S. Dr. G Ravi Kumar. (2016) "Sensorless Speed Control Of Brushless Dc Motor Using Fuzzy Controller," International Conference on Electrical, Electronics, and Optimization Techniques: 4082–4085.

[5] Z. Yong, W. Man, L. Qi, and Z. Chao. (2016) "The design of BLDCM controller for EMA based on fuzzy PID control," Chinese Control and Decision Conference: 6428–6432.

[6] K. Sarojini Devi, R. Dhanasekaran. (2016) "Improvement of Speed Control Performance in BLDC Motor Using Fuzzy PID Controller," Int. Conf. Adv. Commun. Control Comput. Technol, 978: 1- 5.

[7] P. Pillay and R. Krishnan. (1988) "Modeling of Permanent Magnet Motor Drives," IEEE Trans. Ind. Electron, 35(4): 537–541.

[8] B. S. K. K. Ibrahim et al. (2012) "PI-Fuzzy Logic Control for 3 Phase BLDC Motor for Electric Vehicle Application," 6th European Modelling Symposium: 84–88.

[9] R. Arulmozhiyal. (2012) "Design and Implementation of Fuzzy PID Controller for BLDC Motor using FPGA," International Conference on Power Electronics, Drives and Energy Systems: 1–6.

[10] C. Xu-hui, M. L. Rahman, and Z. Yin. (2016) "Adaptive Fuzzy PID Speed Control of DC Belt Conveyor System," 17th International Conference on Software Engineering, Artificial Intelligence, Networking and Parallel/Distributed Computing: 487–490.

[11] N. Farouk and T. Bingqi. (2012) "Application of self-tuning fuzzy PID controller on the AVR system," International Conference on Mechatronics and Automation: 2510–2514.

[12] N. Parhizkar, M. Shafiei, and M. B. Kouhshahi. (2011) "Direct Torque Control of Brushless DC Motor Drives with Reduced Starting Current Using Fuzzy Logic Controller," International Conference on Uncertanity Reasoning and Knowledge Engineering: 4–7.

[13] S. P. and Prof.Dr.A.Sivasubramanian. (2011) "Speed Control Of Brushless Dc Motor With PI And Fuzzy Logic Controller Using Resonant Pole Inverter," PES Innovative Smart Grid Technologies: 334–339.

[14] G. Tan, W. Shu, and M. Liu. (2015) "The Application of Fuzzy Control in Brushless DC Motor for Pure Electric Vehicle," in International Conference on Communication Problem-Solving: 560–562.

[15] M. . E. Blessy and M. Murugan. (2014) "Modelling and controlling of BLDC Motor Based Fuzzy Logic," International Conference on Information Communication and Embedded Systems. 978: 1–6.

[16] K.Premkumar and Dr.B.V.Manikandan. (2013) "Adaptive fuzzy logic speed controller for Brushless DC motor," International Conference on Power, Energy and Control: 290–295.

[17] ArundhathiShyam and F. D. J. L. (2013) "A Comparative Study on the Speed Response of BLDC Motor Using Conventional PI Controller , Anti-windup PI Controller and Fuzzy Controller," International Conference on Control Communication and Computing: 68–73.

[18] U. Neethu and V. R. Jisha (2012) "Speed Control of Brushless DC Motor : A Comparative Study," International Conference on Power Electronics, Drives and Energy Systems: 1–5.

[19] H. Kahveci, H. I. Okumus, and M. Ekici. (2013) "A Fuzzy Logic Speed and Current Controller For Br ushless DC Motors," IEEE INISTA, Turkey: 1–5.

[20] M. Singh and A. Garg. (2012) "Performance Evaluation of BLDC Motor with Conventional PI and Fuzzy Speed Controller," India International Conference on Power Electronics: 1–6.

[21] A. Jaya, Melinda Badriatul Fauziah, G. Prabowo, E. Purwanto, F. D. Murdianto, and M. R. Rusli. (2017) "Design of PID-Fuzzy for Speed Control of Brushless DC Motor in Dynamic Electric Vehicle to Improve Steady-State Performance," International Electronics Symposium on Engineering Technology and Applications: 179–184.

[22] N. N. Baharudin and S. M. Ayob. (2015) "Brushless DC Motor Drive Control using Single Input Fuzzy PI Controller (SIFPIC)," Conference on Energy Conversion: 13–18.

[23] M. F. Z. Abidin, D. Ishak, and A. H. A. Hassan. (2011) "A Comparative Study of PI , Fuzzy and Hybrid PI- Fuzzy Controller for Speed Control of Brushless DC Motor Drive," International Conference on Computer Application and Industrial Electronics: 189–194.

[24] E. Gowthaman, V. Vinodhini, M. Y. Hussain, S. K. Dhinakaran, and T. Sabarinathan. (2017) "Speed Control of Permanent Magnet Brushless DC Motor Using Hybrid Fuzzy Proportional plus Integral plus Derivative Controller," Energy Procedia, 117: 1101–1108.

[25] P. K. Khanke and S. D. Jain. (2015) "Comparative Analysis of Speed Control of BLDC Motor Using PI , Simple FLC and Fuzzy – PI Controller," International Conference on Energy Systems and Applications: 296–301.

[26] M. M. Kamal, D. (Mrs.)Lin. Mathew, and D. S. Chatterji. (2014) "Speed Control of Brushless DC Motor Using Fuzzy Based Controllers," Students' Conference on Electrical, Electronics and Computer Science: 1–6.

[27] K. A., A. A. Rajan, and P.Rajalakshmi. (2013) "Mathematical modelling and Speed control of a Sensored Brushless DC motor using Intelligent controller," International Conference On Emerging Trends in Computing communication and Nanotechnology: 211–216.

[28] M. S. Kalavathi and C. S. R. Reddy. (2012) "Performance Evaluation of Classical and Fuzzy Logic Control Techniques for Brushless DC Motor Drive," International Power Modulator and High Voltage Conference: 488–491.

[29] R. Arulmozhiyal and R.Kandiban. (2012) "Design of Fuzzy PID Controller for Brushless DC Motor," International Conference on Computer Communication and Informatics: 1–7.

[30] D. R. Arulmozhiyal and R.Kandiban. (2011) "An Intelligent Speed Controller for Brushless DC Motor," 7th IEEE Conference On Industrial Electronics and Application: 16–21.

[31] G. Junshan, Z. Sun, and J. Wang. (2010) "Design and Simulation of Fuzzy PID Controller," International Conference on E-Product, E-Service, and E- Entertainment: 4–7.

[32] S. Fan and H. Zhu. (1854) "Simulation Of The Fuzzy Pid Control System For Brushless Dc Motors Based On MATLAB," International Conference on Automatic Control and Artificial Intelligence: 1854–1857.

[33] P. Xue, H. Wang, J. Hou, Li, and Wenchao. (2012) "Based on the fuzzy PID brushless DC motor control system design," International Conference on Measurement, Information and Control: 703–706.

[34] J. Jing, Y. Wang, and Y. Huang. (2016) "The Fuzzy-PID Control of Brushless DC Motor," International Conference on Mechatronics and Automation: 1440–1444.

[35] K. S. Devi, R. Dhanasekaran, and S.Muthulakshmi. (2016) "Improvement of Speed Control Performance in BLDC Motor Using Fuzzy PID Controller," International Conference on Advanced Communication Control and Computing Technologies: 380–384.

[36] S. Boumazbar, S. Bouall, and J. Hagg. (2015) "Co-simulation and Rapid Prototyping of Fuzzy Supervised PID controllers based on FPGA-Nexys2 Board," 7th International Conference on Modelling, Identification and Control: 3–8.

[37] D. Liu, C. Xia, M. Zhang, and Y. Wang. (2007) "Control of Brushless DC Motor Using Fuzzy Set Based Immune Feedback PID Controller," Industrial Symposium on Industrial Electronics: 1045–1049.

[38] A. P. K.M and Usha Nair. (2017) "An Intelligent Fuzzy Sliding Mode Controller for a BLDC Motor," International Conference on Innovative Mechanisms for Industry Applications:274–278.

[39] S. Agrawal and Vivek Shrivastava. (2017) "Particle Swarm Optimization of BLDC Motor With Fuzzy Logic Controller for Speed Improvement," 8th International Conference on Computing Communication and Network Technology: 1–5.

[40] H. Wang, Y. Shu, P. LI, and D. Kang. (2017) "Double Closed Loop Control for BLDC Based on Whole Fuzzy Controllers," 2nd International Conference on Computational Intelligence and Application: 487–491.

[41] I. F. Davoudkhani. (2016) "Adaptive Speed Control of Brushless DC (BLDC) Motor Based on Interval Type-2 Fuzzy Logic,"24th Iranian Conference on Electrical Engineering:1119–1124.

[42] V. Nigam, S. Hussain, and S. N. Agarwal. (2016) "A Hybrid Fuzzy Sliding Mode Controller for a BLDC Motor Drive," 1st IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems:1–4.

[43] Z. Wang, C. Liu, X. Song, Z. Song, and Z. Yang. (2016) "Improved Variable Universe Fuzzy Pid Application In Brushless Dc Motor Speed Regulation System," International Conference on Machine Learning and Cybernetics, South Korea: 459–463.

[44] G. Deying and Z. Jinquan. (2014) "Speed control of BLDCM Based on Compensated Fuzzy Neural Network," :4541–4544.

[45] C. Navaneethakkannan and Dr.M.Sudha. (2013) "Comparison of Conventional & PID Tuning of Sliding Mode Fuzzy Controller for BLDC Motor Drives," International Conference on Computer Communication and Informatics: 4–9.

[46] V. Verma, V. Harish, and R. Bhardwaj. (2012) "Hybrid PI Speed Controllers for Permanent Magnet Brushless DC Motor," 5th India International Conference on Power Electronics:1–5.

[47] A. Rubaai and P. Young. (2011) "EKF-Based PI/PD-Like Fuzzy-Neural-Network Controller for Brushless Drives," IEEE Trans. Ind. Appl., . 47(6): 2391–2401.

[48] C. S. R. Reddy and M. S. Kalavathi. (2011) "Improved Performance of a Novel SMC-Fuzzy Controller for DTC Brushless DC Motor Drive for Precise Speed Regulation," 9th International Conference on Power Electronics and Drive: 873–880.

[49] A. Rubaai, M. J. Castro-sitiriche, and A. R. Ofoli. (2008) "Design and Implementation of Parallel Fuzzy PID Controller for High-Performance Brushless Motor Drives : An Integrated Environment for Rapid Control Prototyping," IEEE Trans. Ind. Appl., 44(4): 1090–1098.

[50] A. H. Niasar, A. Vahedi, and H. Moghbelli. (2005) "Speed Control of a Brushless DC Motor Drive via Adaptive Neuro-Fuzzy Controller Based on Emotional Learning Algorithm," International Conference on Electrical Machines and Systems: 230–234 Vol. 1.

[51] C. Xia, P. Guo, T. Shi, and M. Wang. (2004) "Speed Control of Brushless DC Motor Using Genetic Algorithim Based Fuzzy Controller," International Conference on Intelligent Mechatronics and Automation, China: 460–464.

[52] Ushakumari, S.Sankaran, R. Nair, P.S Chandramohanan (2001) "Adaptive Neuro-Fuzzy Controller for Improved Performance,"International Fuzzy Systems Conference:493–496.