Parameter Estimation and Comparative Analysis of Control Design Techniques for BLDC Hub Motor

Shivanand Pal
Societal Electronics Group
CSIR-Central Electronics
Engineering Research Institute
(CEERI)
Pilani; Rajasthan; India
palshiva2012@gmail.com

Akshit Patel
Electrical, Electronics
and Instrumentation Engg.
Birla Institute of Technology
and Science Pilani
Pilani; Rajasthan; India
f20180094@pilani.bits-pilani.ac.in

Aditya Mandar Jabade
Electrical, Electronics
and Instrumentation Engg.
Birla Institute of Technology
and Science Pilani
Goa; India
f20180436@goa.bits-pilani.ac.in

Kartheek Miduthuru
Electrical, Electronics
and Instrumentation Engg.
Birla Institute of Technology
and Science Pilani
Hyderabad; India
f20180104@hyderabad.bits-pilani.ac.in

Gaurav Sahu
Electronics and
Communication Engineering
B K Birla Institute of
Engineering and Technology
Pilani; Rajasthan; India
gauravsahu.87@gmail.com

B. A. Botre
Societal Electronics Group
CSIR-Central Electronics
Engineering Research Institute
(CEERI)
Pilani; Rajasthan; India
bhau@ceeri.res.in

Brijendra Kumar Verma
Societal Electronics Group
CSIR-Central Electronics
Engineering Research Institute
(CEERI)
Pilani; Rajasthan; India
brijverma@ceeri.res.in

S. A. Akbar chief scientist
~~*Societal Electronics Group*~~
CSIR-Central Electronics
Engineering Research Institute
(CEERI)
Pilani; Rajasthan; India
saakbar@ceeri.res.in

***Abstract*—Brushless DC (BLDC) motors have become the optimal choice for high-precision controller implementation in industrial applications. This paper presents a detailed analysis of a hub BLDC motor used in low power electric vehicles right from parameter estimation to the implementation of speed control techniques. The parameter estimation is followed by the development of the mathematical model of the BLDC motor. The conventional PID technique and the genetic algorithm-based tuning are applied to the mathematical model. Further physical model of the motor is constructed and simulated for broadly 3 control methods: Conventional PID, Genetic algorithm, and self-tuning Fuzzy logic method. The purpose of the research is to provide a comparative analysis of these control strategies and to identify the optimal one for speed-control of the BLDC hub motor. Results show that the proposed, adaptive Fuzzy logic technique is the best control design for practical implementation.**

***Index Terms*—Brushless DC Motor (BLDC), Mathematical Modelling, Genetic Algorithm (GA), PID, MATLAB, Simulink, Fuzzy Logic, Self-Tuning PID Controller**

I. Introduction

High-performance motor drives are indispensable to the ever-growing fields of industrial control, robotics, aviation, and especially to the future of travel i.e. 'Electric Vehicle Systems.' The use of electric motors follows from this industrial requirement. Conventional DC motors are the first choice owing to the excellent on-field characteristics but have a serious limitation when it comes to power dissipation [1]. This is mainly due to the frictional and consequently, heat losses, in the brushes, whereas unwanted electric discharges in the commutator arrangement [1]. As an alternative, induction motors are used in varied applications but problems arise when it comes to requirements of a high-power factor, a high starting torque, and high-speed control.

Considering these issues, the highly efficient 'Brushless DC motor' is the optimal choice, as it provides high torque to weight ratio, more torque per Watt (increased efficiency), less noise, elimination of sparks, and increased reliability. The commutation is done by solid-state switches and the motor is driven by DC voltage. The rotor position is determined by Hall sensors [2] or even otherwise by sensor-less techniques [3]. This establishes the commutation instants. The present paper emphasizes on the use of the BLDC 'Hub' motor in particular by providing its detailed study right from parameter estimation to speed control. Considering the requirements of the control mechanism for the BLDC hub motor, the PID (Proportional Integral Derivative) was the first choice as presented further, owing to its accuracy, integrity, stability, and feasibility. The heuristic approach of Ziegler-Nichols for tuning the PID gains is widely used but it has serious limitations when it comes to robustness, instability, and universal applications across all systems. Thus, this paper brings out novel techniques of tuning the controller like the Genetic algorithm and self-tuning Fuzzy logic control. The genetic algorithm-based approach facilitates achieving the required performance of the system in terms of well-defined cost (objective) functions which are minimized over several

978-1-7281-6916-3/20/$31.00 ©2020 IEEE

iterations. This has an edge over the auto/manual tuning method which requires adjusting the performance now and then. The paper exploits this advantage of evolutionary algorithms for controller designing [4]. The Fuzzy logic-based [5] technique is also dealt with, in this paper to a great detail which creates an adaptive logic controller for the motor. This ensures that the system is controlled well even in cases of uncertainties in parameters and nonlinearities in the environment. The paper aims at providing a comparative analysis of these varied control techniques to attain an optimal solution.

Similar to many contemporary studies regarding the BLDC motor, the unavailability of motor parameters was the principal challenge in this research. The only available information was the current rating 10A, Voltage rating 24V and the number of pole pairs 10. To study the motor behavior and to obtain the speed vs torque and motor efficiency, the Drum Break arrangement was designed. Using this experimental set-up the torque, speed, and current were observed, by using these parameters the following parameters were derived mathematically: moment of inertia (J), friction coefficient (B), back EMF (Electromotive Force) voltage constant (K_e) and torque constant (K_t). Further, this knowledge of parameter values was used to construct the mathematical as well as the physical model of the BLDC motor in MATLAB-Simulink. The mathematical model was tuned using a linearized method coupled with manual ones and separately by genetic algorithms to obtain the values of K_p , K_i, and K_d. The validity of this tuning was tested by simulating the physical model, for these values of PID constants. The physical model was further tuned using the adaptive fuzzy-logic technique.

II. Experimental Setup

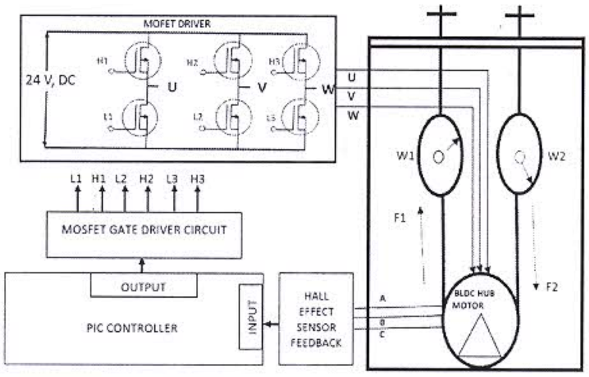

Fig. 1. Experimental setup of BLDC hub motor

To rotate the motor continuously the controller energizes the motor winding by solid-state switches as shown in Fig. 1. In the proposed experimental set up BLDC hub motor is operated in three-phase. The experimental setup is implemented using the BLDC hub motor driver circuit, which includes the MOSFET driver circuit, electronic controller, Hall Effect sensor, and brake drum arrangement. Hall Effect sensors are present in the BLDC hub motor, which provides the position of the rotor. The speed of the BLDC hub motor can be increased or decreased based on the requirements by using the electronic circuit. Using brake drum arrangement the BLDC hub motor parameters are derived and calculated. Also, using this set up the back EMF voltage and phase current waveforms are observed on the oscilloscope for different loading conditions. Also, the efficiency of the motor was calculated by calculating the input and output power of the motor.

The experimental setup is controlled by using the PIC (Peripheral Interface Controller) controller. Hall Sensor signals are input to the controller, which generates the PWM (Pulse Width Modulation) pulses through which the commutation sequence is obtained. On completion of each cycle, the PIC controller generates six PWM signals which are the inputs to MOSFET driver IC.

The duty cycle of the PWM signal is controlled by the PIC controller which corresponds to the throttle voltage amplitude required to maintain the desired speed. The trapezoidal back EMF wave-forms are generated by the inverter circuit. Torque is generated by the interaction between the magnetic field generated by the stator coils and the permanent magnet.

TABLE I
Parameter Table

Parameter	Value	Unit	Symbol
Per phase resistance	0.155	Ohm	R_a
Per phase inductance	0.161	mH	L_a
Moment of Inertia	4.88e-4	Nm/s^2	J
Damping coefficient	5.15e-3	Nms/rad	B
Torque constant	0.2969	Nm/A	K_t
Back EMF constant	0.1546	Vs/rad	K_e/K_b
Max. Flux linkage	16.765	mWb	Ψ_m
Number of pole pairs	10	-	PP

A. Motor Gear Ratio

A planetary gear or epicyclic gear arrangement consists of three kinds of gears sun, planet and ring mounted in such a way that the center of planet gear revolves around that of sun. A carrier connects the centers of all three planetary gears and rotates to carry the planet gear around the sun gear. To analyze the action of the gear train on the input and output torque, speed it is necessary to calculate the gear ratio. Many configurations can be created by locking one kind of gear and using others for input and output [6]. For the ring gear locked with sun gear as input and carrier output, which is the kind of operation in this study, the gear ratio is given by:

$$GearRatio = 1 + \frac{N_r}{N_s} \quad (1)$$

N_r is the number of teeth on the ring gear and N_s is the number of teeth on the sun gear. For this motor, N_r=93 and N_s=23. Hence the gear ratio is 4.57.

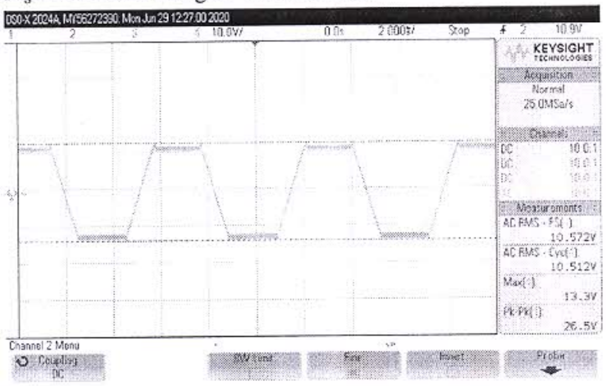

Fig. 2. Peak-Peak Value Of Back EMF

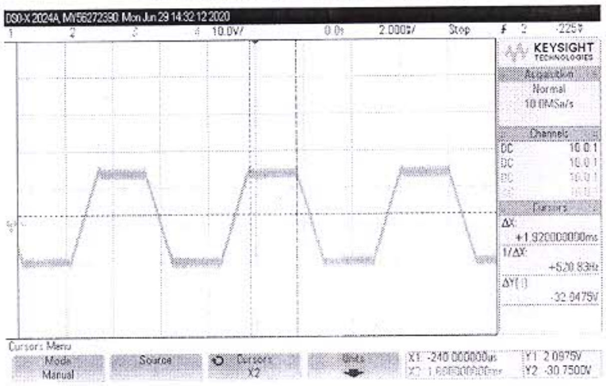

Fig. 3. Time for which Back EMF is constant

B. Speed Calculations

The no-load speed was measured by the tachometer as 215 RPM i.e. 22.51 rad/s. However, this is the output speed of the gear train. Thus to obtain the actual rotor speed, the gear ratio is used. The rotor speed is 4.5 times the measured speed and is hence equal to 102.87 rad/s.
From the back EMF profile obtained on the oscilloscope Fig. 2 - 3 the frequency(f) obtained is 159.72 Hz. The number of pole pairs (P) is 10. Hence the angular speed can be estimated as

$$\omega = \frac{60f}{P} \tag{2}$$

Thus estimated angular speed is 100.3529 rad/s. This is in close agreement to the measured value which validates the correctness of the back-EMF profile.

C. Methods of Parameter Estimation

The per-phase resistance and inductance are measured by simply using the ohmmeter and inductance meter respectively across the line-to-line nodes and dividing the value by two [7]. The torque constant and the back EMF constant are measured according to the definitions which is

- K_t = Ratio of Torque to Phase current
- K_e = Ratio of Peak phase voltage to Angular speed

Of particular interest is the measurement of B and J. The damping coefficient B is calculated by rotating the motor at a constant speed. Thus the torque equation becomes τ = Bω and from the known values of torque and angular speed, B can be known [7]. For J, the motor is first run at a steady speed, and then it is switched off. The time taken for the speed to decrease to 36.8% is noted. This time constant is mathematically equal to B/J. Thus, J can be estimated from the known value of the time constant and B [7]. All the parameters are tabulated in Table I.

III. Mathematical Model and Transfer Function of BLDC Motor

A. Transfer Function Estimation

The transfer function is the important hypothesis of the control system and such types of mathematical models are used in the automation based on the control system. The study assumes that the three-phase BLDC hub motor is controlled in two-phase conduction mode. The equivalent circuit of BLDC Hub Motor is as shown in Fig. 5. At a time only two phases are active either AB or BC or CA, one positive and the other negative.
Once the parameters are known, mathematical modeling is essential to understand the behavior of the system. Thus, it is required to derive the transfer function for the BLDC motor. Generally, the mathematical model of a Brushless DC motor is on the similar lines of that of the brushed conventional DC motor. The significant addition is in the phases involved which directly affect the overall results of the BLDC model. The phase distinctly affects the resistive and the inductive nature of the BLDC arrangement. For BLDC motor the mechanical and electrical time constants are vital modeling parameters. The voltage equation of a brushless DC (BLDC) motor is given by the following equation:

$$V = Ri + L_s\frac{di}{dt} + K_e\omega \tag{3}$$

where V is the phase voltage, R is the phase resistance, L_s is the synchronous inductance, and K_e is the back electromotive force (BEMF) constant. The net torque equation at no load is given by [8]:

$$\tau = J\frac{d\omega}{dt} + B\omega \tag{4}$$

Based on the symmetrical and three-phase arrangement, the transfer function of the BLDC motor is:

$$\frac{\omega}{V}(s) = \frac{K_t}{(JL_a)s^2 + (JR_a + BL_a)s + (BR_a + K_bK_t)} \tag{5}$$

$$\frac{\omega}{V}(s) = \frac{0.2969}{(7.859e-8)s^2 + (7.649e-5)s + 0.0467} \tag{6}$$

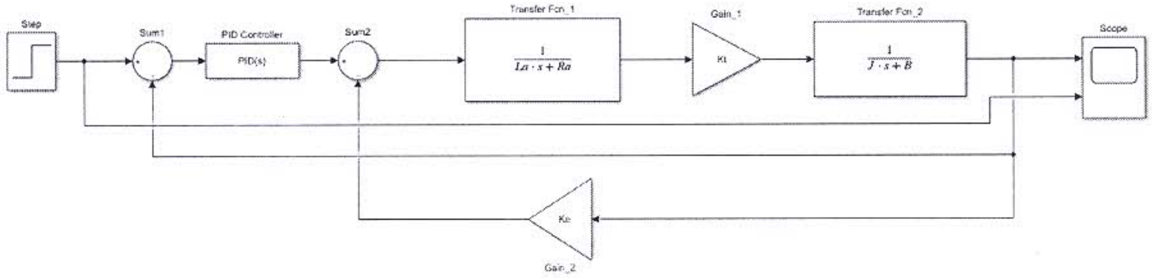

Fig. 4. Simulink Model for Transfer Function

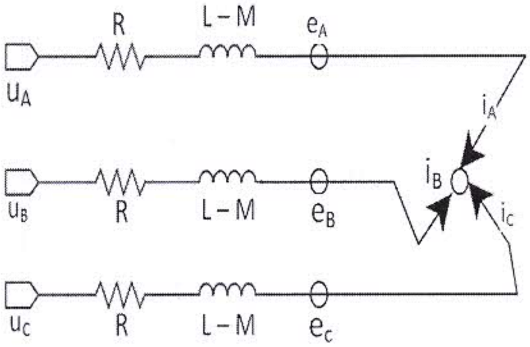

Fig. 5. Equivalent Circuit of BLDC hub motor

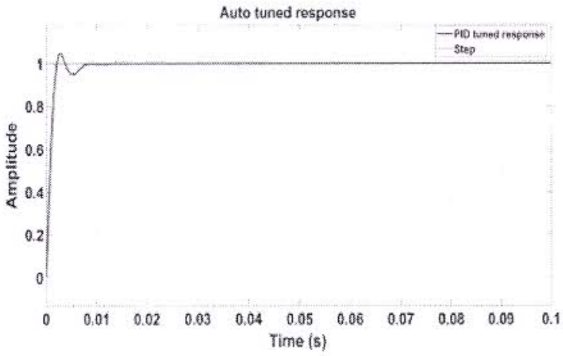

Fig. 6. Simulink Model Result

B. Simulink Model of Transfer Function

The Simulink block diagram model is shown in Fig. 4. The input is the desired angular speed (ω). At the Sum1 block, this is compared to the output angular speed and the error is fed to the PID controller. This in turn actuates the voltage signal (v) which is compared with the back EMF (e) at the block Sum2. The Transfer Fcn1 block converts this error from Sum2, to phase current fed to Gain1 block (3). The output of Gain1 is the electromagnetic torque (τ_e). The next Transfer Fcn2 block converts this electromagnetic torque to angular speed ω which is the required output (4).

$$\tau = K_t i \tag{7}$$

$$e = K_e \omega \tag{8}$$

IV. PID Tuning of Mathematical Model

A. Simulink Linearised Tuning

The block diagram model depicted in Fig. 4 is initially linearized with the help of PID controller block in Simulink. It is then tuned for a robust closed loop response. The constants obtained were:

$$K_p = 0.3402, K_i = 170.9125, K_d = 0.000167$$

The closed loop response is shown in Fig. 6.

B. Genetic Algorithm based Tuning

The genetic algorithm was implemented in MATLAB for two cost functions [9]. The population size was selected to be 25 and the generation size was 10. The optimization of the two cost functions gave out values of constants K_p, K_i, and K_d for each of the two cost functions. These sets of constants were implemented in the physical model and its speed tracking performance was analyzed.

The cost functions were:

1) LQR:

$$\sum_{n=0}^{n=\frac{t}{\Delta t}} (Q(1 - y(n\Delta t))^2 + Ru^2(n\Delta t))\Delta t \tag{9}$$

Here the input is a unit step function, y is the system output which is a continuous function in time. Thus $1 - y$ is the steady-state error. u is the control input. t=20 which is the time-limit of the code. Δt is sampling time and is set to 0.001 Q and R are the weights to each of $1 - y$ and u which were set to be 1 and 0.01 respectively [9].

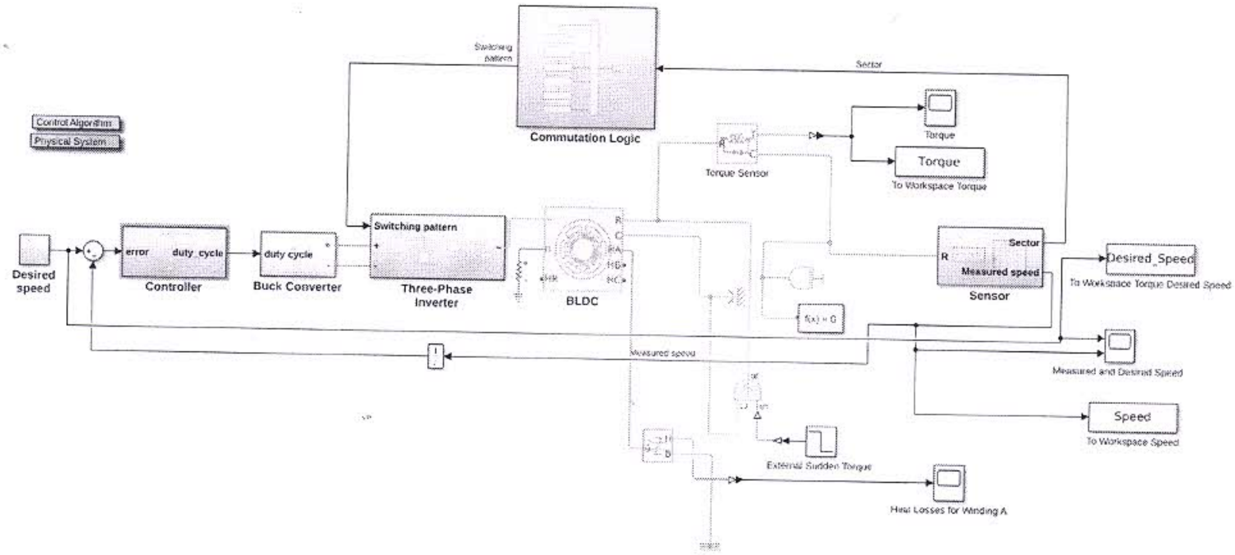

Fig. 7. Physical Model of BLDC hub motor in MATLAB SIMULINK

2) Cost function 2:

$$\frac{1}{x(ess - ess_d) + y(tr - tr_d)} \tag{10}$$

Here ess and tr are the variables steady state-error and rise time respectively. And ess_d and tr_d are the predefined value of the steady-state error and rise time respectively, for the unity feedback uncontrolled mathematical model. x and y are the weights for both and are set to 1. The following constants were achieved after optimization of the respective cost functions:

LQR: K_p=1.2065 K_i=2.1291 K_d=0.0057

Cost function2: K_p=3.65 K_i=2.0855 K_d=0.0026

V. Physical Model of BLDC Hub Motor

The complete logic designed [10] in MATLAB Simulink can be seen in Fig. 7. Closed loop controller was designed with the help of PID. Four different algorithms were used for tuning PID constants.

1) Normal PID Tuning – PID Constants were tuned manually
2) Genetic Algorithms – Two sets of constants were obtained by minimizing two cost functions with Genetic Algorithm explained in section IV-B
3) Fuzzy Controller – Fuzzy Logic was used to tune fuzzy PID constants also called the self-tuning fuzzy controller

All parameters obtained in section IV-B were directly entered into the Simscape Electrical library BLDC motor block. Additionally, flux linkage [11], [12] was calculated from the back emf profile as it is a required input for the block. Back EMF Profile of simulated motor obtained by developing circuits in Simulink can be seen in Fig. 8 which completely matches that obtained from experiment Fig. 2 - 3. Also, mutual inductances for stator windings were neglected to keep results in tune with that of the simplified mathematical model.

In the next section, Fuzzy Logic is discussed. In section V-B Torque-Speed, Speed-time and Voltage-Time characteristics of the motor with different algorithms obtained using the physical model are discussed and are used to compare different algorithms. All results have been obtained on no-load condition. The load can be applied by entering the value in the inertia block.

A. Self-Tuning Fuzzy Logic Controller

Fuzzy logic is a method formed to emulate the human reasoning process where truth-value, unlike conventional

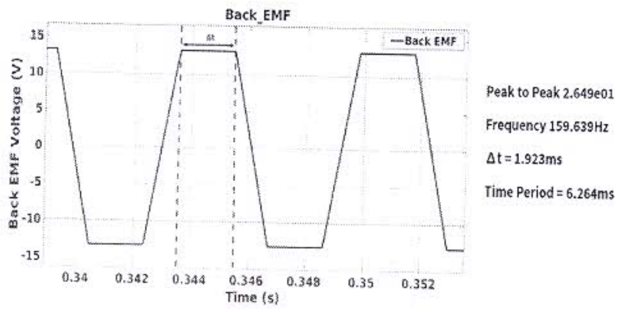

Fig. 8. Back EMF profile obtained from SIMULINK

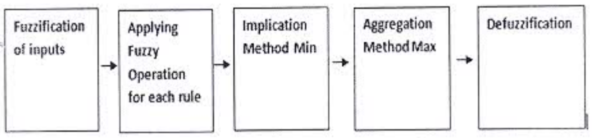

Fig. 9. Fuzzy Inference Process

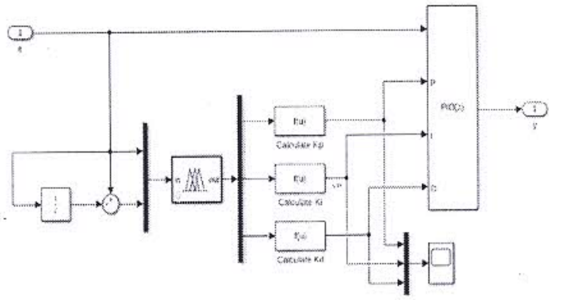

Fig. 10. Fuzzy Implementation MATLAB SIMULINK using Fuzzy Toolbox

methods, can be any real number between 0 and 1 (both inclusive) i.e., partial truth can be configured rather than being completely true or false. Fuzzy control has multiple benefits over other controllers. It does not require a fixed model of the system. It uses a set of rules defined in the form of a table for mapping inputs to different outputs and finally arrives at a decision. (Table II-IV) [13], [14]. Unlike traditional multi-valued logical systems, it can model nonlinear systems of arbitrary complexity and also employ experience of the individuals while building it. Fuzzy logic was used to tune PID constants which is known as self-tuning PID control. Pure Fuzzy logic controller and Hybrid Fuzzy Logic Controllers [15], [16]

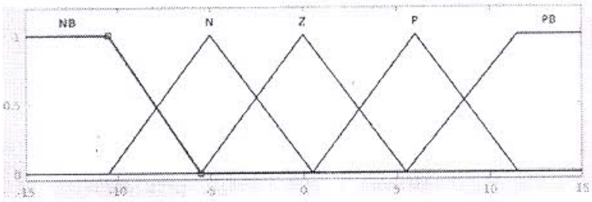

Fig. 11. Input Membership Functions

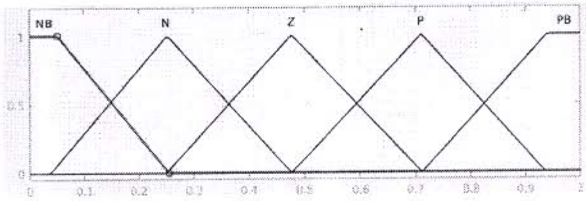

Fig. 12. Output Membership Functions

TABLE II
FUZZY RULES FOR K_P GAIN

e\\Δe	NB	N	Z	P	PB
NB	NB	NB	NB	N	Z
N	NB	N	N	N	Z
Z	NB	N	Z	P	PB
P	Z	P	P	P	PB
PB	Z	P	PB	PB	PB

TABLE III
FUZZY RULES FOR K_I GAIN

e\\Δe	NB	N	Z	P	PB
NB	PB	PB	PB	N	NB
N	PB	P	P	Z	NB
Z	P	P	Z	N	NB
P	Z	P	N	N	NB
PB	Z	N	NB	NB	NB

TABLE IV
FUZZY RULES FOR K_D GAIN

e\\Δe	NB	N	Z	P	PB
NB	NB	NB	NB	P	PB
N	NB	N	N	Z	PB
Z	N	N	Z	P	PB
P	Z	N	P	P	PB
PB	Z	P	PB	PB	PB

are other alternatives. The complete fuzzy logic process can be explained in Fig 9. A more detailed figure can be found in [17]. Output membership functions were defined for the Mamdani Fuzzy Inference System [18]. Another available alternative is the Sugeno Inference System [19]. Both differ in the definition of output membership function and the defuzzification process. The Centroid method was used for defuzzification. Details of other defuzzification methods in MATLAB Simulink like Bisector, Middle of Maximum(MOM), Smallest of Maximum(SOM) and Largest of Maximum(LOM) can be found at [20].

Fuzzy implementation can be found in Fig. 10. First, the error is taken as input to the controller marked in Fig 10 as e. The input was delayed by one sample held for one sample period to create another input, i.e., rate of change of error, Δe. For both the inputs triangular membership functions were used to characterize the fuzzy sets N (Negative), Z (Zero), and P (Positive). L trapezoidal function was used to categorize any input above 15 as PB (Positive Big) and R trapezoidal function for categorizing input below -15 as NB (Negative Big). This allows us to have optimum results for the system when input is between the specified range(in this case -15 to 15). Membership function for both the inputs e and Δe is depicted in Fig. 11. Similarly, membership function for all outputs K'_P, K'_I, K'_D can be found in Fig. 12. Rules for each output can be found in Table II-IV. Outputs of the Fuzzy Inference System (FIS) will be distributed over 0 to 1. So, by defining maximum and minimum of all three constants, and by deriving final constants as shown in (11) (12) (13).

$$K'_P = \frac{K_P - K_{P_{min}}}{K_{P_{max}} - K_{P_{min}}}, K_P = (K_{P_{max}} - K_{P_{min}})K'_P + K_{P_{min}} \quad (11)$$

$$K'_I = \frac{K_I - K_{I_{min}}}{K_{I_{max}} - K_{I_{min}}}, K_I = (K_{I_{max}} - K_{I_{min}})K'_I + K_{I_{min}} \quad (12)$$

$$K'_D = \frac{K_D - K_{D_{min}}}{K_{D_{max}} - K_{D_{min}}}, K_D = (K_{D_{max}} - K_{D_{min}})K'_D + K_{D_{min}} \quad (13)$$

output can be restricted to the range defined for the system considered. These limits were defined by first tuning normal PID and then selecting a suitable range for constants. Adding to that output execution time and behavior can be tuned by altering this range.

B. Comparison of Different Algorithm

First speed vs torque characteristics was obtained using each algorithm as shown in Fig. 13. The graph is a bit oscillatory when speed is reaching reference due to respectively more changes in torque as compared to changes in speed. The maximum value of torque efforts by each algorithm was noted. In this case, it was for PID constants obtained from Genetic algorithm by minimizing the cost function (10). That value was found to be 0.0395 Nm.

A sudden load torque of 0.1096 Nm was applied at 1s in each case to test the robustness of each controller. The Speed, Voltage, and Current characteristics were obtained. The speed characteristics obtained can be seen in Fig. 14-17

Compiled data can be found in Table V. Maximum current, voltage, and torque effort required by each controller while handling sudden load and behavior while tracking reference speed were noted. Priority number was allotted to each algorithm based upon speed time graphs in terms of

TABLE V
COMPILED DATA

Controller	*Maximum Torque**	*Maximum Current**	*Maximum Voltage**	*Priority no. wrt speed response***
Normal PID	0.02729	1	3	3
Fuzzy PID	0.02229	0.8	3	1
GA LQR	0.0276	0.82	3	2
GA Cost function2	0.0395	1.25	3.25	4

* The one requiring a minimum amount of maximum voltage, current, and torque while handling disturbance and tracking reference is said to be the best performing controller.
** Lower the priority number, higher the performance index with respect to tracking speed. Thus 1 corresponds to the best controller.

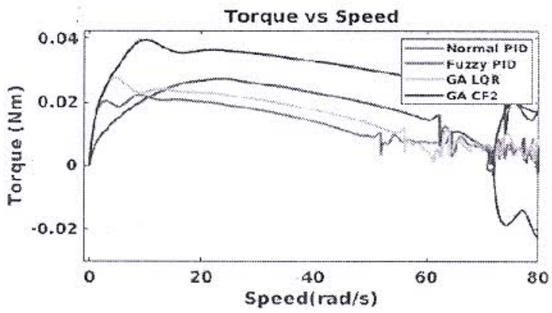

Fig. 13. Torque Vs Speed of Motor with different algorithm

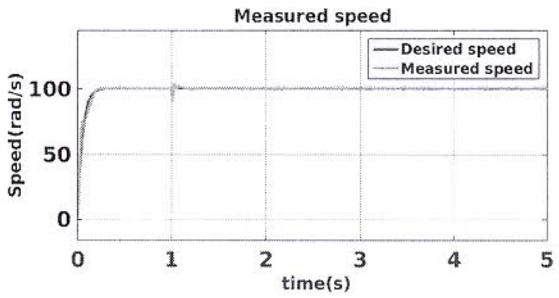

Fig. 14. Speed vs Time with Normal PID

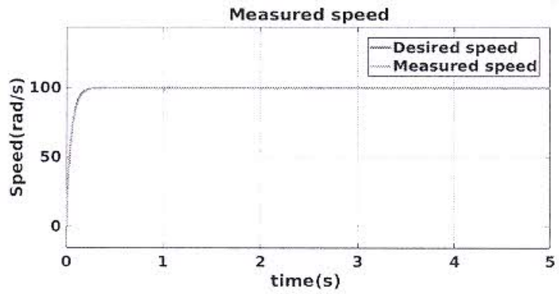

Fig. 15. Speed vs Time with Self Tuning Fuzzy Controller

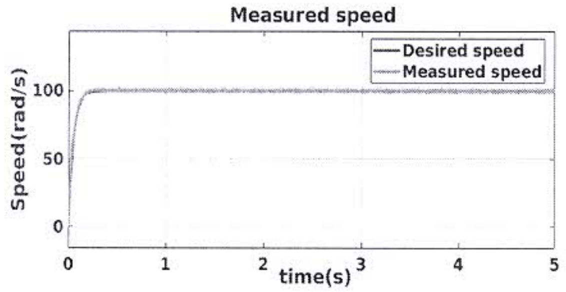

Fig. 16. Speed vs Time for LQR cost function (9) with GA

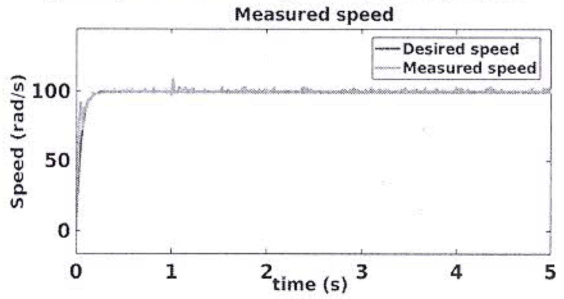

Fig. 17. Speed vs Time for cost function 2 (10) with GA

rise time, overshoot, and speed tracking when sudden load torque was applied.

It was found that fuzzy required minimum efforts of all in terms of torque, current, and voltage. Also, it was the smoothest one to track reference speed and quickest to reach back to the reference on the application of sudden load. Normal PID tuning constants were as good as the ones obtained from LQR cost function but required more current and had some error while rising to reference speed when compared to the latter. According to this, all algorithms were ranked as shown

1) Fuzzy controller
2) Genetic Algorithm with LQR cost function (9)
3) Normal PID
4) Genetic Algorithm with cost function (10)

Constants obtained from Genetic algorithm were taken directly from the mathematical model and applied to the physical model which might add to some error but even then, fuzzy would outrun Genetic Algorithm as a fixed set of PID constants is not robust in systems where parameters are uncertain and if there is some sort of lag in the model. Thus only using pure PID in real applications such as low power electric vehicle, it fails to accurately have a velocity control as also mentioned in [21].

VI. Conclusion

In this paper, the systematic procedure was discussed for designing closed-loop control of BLDC hub motor from parameter estimation to defining advanced closed-loop control algorithms. Genetic Algorithm was used to minimize two cost functions to have a targeted behavior. Self Tuning Fuzzy logic was applied to achieve best-optimized solutions in the systems where parameters are uncertain and control with a fixed set of PID constants does not suffice. Extensive tests and comprehensive comparison was performed by using Mathematical and Physical Model of the motor. It was found that the self-tuning Fuzzy technique, results in the best performance and is the most suitable technique for real-time applications out of these, where parameters of the system are subject to change.

Acknowledgment

The authors thank Director CSIR-CEERI Pilani, for his guidance and availing the lab facilities. The authors would also like to thank Dr. S A Akbar, Chief Scientist, CEERI-Pilani; Dr. Prasant Kumar Pattnaik, Assistant Professor, Department of Electrical Engineering, BITS Pilani Hyderabad Campus; team members of Cyber Physical System lab and CSIR-CEERI for their constant help and support. Authors would also like to acknowledge the financial support by CSIR.

References

[1] M. Shamseldin and A. El-Samahy, "Speed control of bldc motor by using pid control and self-tuning fuzzy pid controller," 09 2014.

[2] T. Nama, A. K. Gogoi, and P. Tripathy, "Application of a smart hall effect sensor system for 3-phase bldc drives," in *2017 IEEE International Symposium on Robotics and Intelligent Sensors (IRIS)*, pp. 208–212, 2017.

[3] C. K. Lad and R. Chudamani, "Sensorless brushless dc motor drive based on commutation instants derived from the line voltages and line voltage differences," in *2013 Annual IEEE India Conference (INDICON)*, pp. 1–5, 2013.

[4] M. Mjahed, "Pid controller design using genetic algorithm technique," *Proceedings of the ICICR*, pp. 1–4, 2013.

[5] "What is fuzzy logic?." https://www.mathworks.com/help/fuzzy/what-is-fuzzy-logic.html. Accessed: June 16, 2020.

[6] A. L. P. Gustavsson Mårdestam, "Efficiency analysis of a planetary gearbox," 2010. Dissertation.

[7] G. Chandramouleeswaran, B. Abhi, V. Anand, S. Aravind, R. Nandhini, and S. Patnaik, "Dc position control system – determination of parameters and significance on system dynamics," vol. 03, 03 2012.

[8] T.-Y. Ho, F.-T. Liu, G.-W. Ho, and Y.-R. Lin, "The implementation of a measurement system for brushless dc motor parameters," *International Journal of Green Energy*, vol. 14, no. 12, pp. 983–995, 2017.

[9] T. Peters, "Data-driven science and engineering: machine learning, dynamical systems, and control: by sl brunton and jn kutz, 2019, cambridge, cambridge university press, 472 pp.,£ 49.99 (hardback), isbn 9781108422093. level: postgraduate. scope: textbook.," 2019.

[10] "Design-motor-controllers-with-simscape-electrical." https://github.com/mathworks/Design-motor-controllers-with-Simscape-Electrical, GitHub. Retrieved June 16, 2020.

[11] R. Campa, E. Torres, F. Salas, and V. Santibáñez, "On modeling and parameter estimation of brushless dc servoactuators for position control tasks," vol. 17, 07 2008.

[12] "Bldc, three-winding brushless dc motor with trapezoidal flux distribution." https://www.mathworks.com/help/physmod/sps/ref/bldc.html. Accessed: June 16, 2020.

[13] M. Aliyari Shoorehdeli, H. Shoorehdeli, M. Teshnehlab, and M. Yazdanpanah, "Velocity control of an electro hydraulic servosystem," pp. 985 – 988, 11 2007.

[14] M. Parnichkun and C. Ngaecharoenkul, "Hybrid of fuzzy and pid in kinematics control of a pneumatic system," vol. 2, pp. 1485 – 1490 vol.2, 02 2000.

[15] K. Sinthipsomboon, I. Hunsacharoonroj, J. Khedari, W. Po-ngaen, and P. Pratumsuwan, "A hybrid of fuzzy and fuzzy self-tuning pid controller for servo electro-hydraulic system," in *Fuzzy Controllers* (S. Iqbal, N. Boumella, and J. C. F. Garcia, eds.), ch. 13, Rijeka: IntechOpen, 2012.

[16] A. Sabir and M. Kassas, "A novel and simple hybrid fuzzy/pi controller for brushless dc motor drives," *Automatika*, vol. 56, 01 2015.

[17] "Fuzzy-inference-process." https://www.mathworks.com/help/fuzzy/fuzzy-inference-process.html. Accessed: June 16, 2020.

[18] E. Mamdani, "An experiment in linguistic synthesis witch a fuzzy logic controller," *International Journal on Man-machine Studies*, vol. 7, pp. 1–13, 01 1995.

[19] M. Sugeno, "Industrial application of fuzzy control," 01 1985.

[20] "Defuzzification-methods." https://www.mathworks.com/help/fuzzy/defuzzification-methods.html. Accessed: June 16, 2020.

[21] R.-F. Fung, Y.-C. Wang, R. Yang, and H.-H. Huang, "A variable structure control with proportional and integral compensations for electrohydraulic position servo control system," *Mechatronics*, vol. 7, pp. 67–81, 02 1997.