Fuzzy Logic Control and PID Controller for Brushless Permanent Magnetic Direct Current Motor: A Comparative Study

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***Abstract*—Electrical machines based on permanent magnet material excitations have been applied in many sectors since they are distinguished by their high torque-to-size ratio and offer high efficiency. Brushless permanent magnetic direct current (BLPMDC) motors are one type of these machines. They are preferable over conventional DC motors. one of the main challengings of the BLPMDC motor drives is the inherited feature of nonlinearity. Therefore, a conventional PID controller would not be an efficient choice for the speed control of such motors. The object of this paper is to design an efficient speed control for the BLPMDC motor. The proposed controller is based on the Fuzzy logic technique. MATLAB/ Simulink has been employed to design and test the drive system. Simulations were carried out for three cases, the first without a controller, the other using conventional control, and the third using expert systems. The results proved the possibility of improving the engine's working performance using the control systems. They also proved that the adoption of expert systems is better than the traditional nonlinear systems. The simulation response shows that the Rise Time(tr) at PID equals 66.306ms, while it equals 19.530ms for the Fuzzy logic controller. Moreover, Overshoot for PID and Fuzzy logic controller are 6.989% and 1.531%, respectively. On the other hand, undershoot is equal to 1.788% and 11.924% for PID and Fuzzy logic controller, respectively.**

***Keywords*—BLPMDC; PID Controller; FLC; Speed Control.**

I. INTRODUCTION

Brushless permanent magnet direct current (BLPMDC) motors have gained considerable attention since they deliver high efficiency, have good reliability, and the need for maintenance is low [1-5]. Such motors have been popular and are being applied in different applications, including industry, household, and aerospace fields. Generally, operations of these applications need a reliable with high efficiency and power density motor [6-10]. As the BLPMDC motors have no windings on their rotor, the mechanical commutating process is replaced by electrical commutating, and the motors can be fed by a power electronic converter or inverter [11-15]. A proper speed controller is required in order to obtain adequate motor performance. The speed controller of the BLPMDC motors can be categorized into three main types, including open loop speed control (constant load), variable load controller, and positioning controller [16-20].

Designing an efficient BLPMDC motor controller has been of interest to many works of literature. Two-speed control methods, i.e., conventional and an optimal auto-tuning PID controller for BLPMDC motor, were comprehensively compared in [21]. Seeking effective work, the motor parameters were experimentally obtained and then used in MATLAB simulation. It was shown that target speed could be efficiently achieved by the auto-tuning controller, and the variation of both torque and current was reduced in the such controller. Using MATLAB/Simulink, a censored closed-loop speed controller for both clockwise and anti-clockwise was discussed in [22]. The controller was tested at a different speed. The obtained results confirmed the validity of the suggested controller. Similarly, two-speed control techniques were adopted and compared in [23], which were self-tuned PID and modified model-reference adaptive control in which the control decision is established based on the compensation between the modified model-reference adaptive and the PID. It was shown that the latter technique delivered better performance than the former. A comparison between conventional PI and digital controllers for BLPMDC motors was conducted in [24]. Both methods were PWM-based controllers. The simulation results were validated by experimental results. It was concluded that the digital controller has instant response speed, and its control algorithm is simple. Such features make the digital controller a good choice for applications in which the ripple of torque/speed profile is not of considerable importance. Moreover, Ref. [25-28] conducted a comparison between P and PI controllers for the BLPMDC motor. The mathematical model of the motor was driven, and MATLAB/SIMULINK was used to build the motor drive models. It was shown that the steady-state error could be overcome, and the overshoot could be reduced by the PI controller. Ref. [26 -30] introduced a current controller for the BLPMDC motor based on a PID controller to control the switching sequences of the MOSFET bridge, and by controlling the current, the speed would be controlled. In order to evaluate the introduced controller, a comparison with the conventional PI and PID speed controllers was conducted. It was revealed that the introduced PID controller was the most efficient among the other controllers.

In order to obtain the desired performance of the motor, its drive system must be efficient. Usually, the PI and PID controllers are used in controlling the speed of the electrical motor due to their uncomplex structures and simple implementations. However, such controllers deliver insufficient performances with nonlinear systems and load disturbances. Thereby, seeking an improvement in the performance of such controllers, BLPMDC motor controllers based on intelligent techniques have emerged. Ref. [25] compared conventional PID and self-tuning Fuzzy PID controllers for BLPMDC motors. It was delivered that the Fuzzy based tuning PID controller has the features of robustness, efficiency, and simple construction. In this contest, Ref. [26] compared three BLPMDC motor controllers, including conventional PID, PID-based Genetic Algorithm tuning, and PID-based Fuzzy Logic tuning controllers. It was stated that the last controller delivered the best performance among the other controllers. In [27], ANN tuning PID and conventional manual tuning PID controllers were compared. Both controllers were built using MATLAB/ SIMULINK. It was delivered that using the ANN for tuning the parameters of the PID controller would enhance the controller performance piratical for nonlinear dynamic conditions. ANN controller based on model reference adaptive control technique was introduced and compared with the conventional PID controller in [29]. It was confirmed that the ANN controller delivered a very good performance for speed tracking, and it was able to minimize the parameter variations impact.

It can be observed that although the PI and PID controllers are not expensive as well as not complex, they are not good candidates for the cause of nonlinear system applications. On the other hand, such a problem would be overcome by adapting motor speed control based on artificially intelligent systems. Therefore, in this paper, Fuzzy Logic will be adapted to design a speed controller for the BLPMDC motor. Considering the evaluation of the proposed speed controller, a comparison of the PID conventional speed controller and the proposed counterpart is carried out. The rest of the paper is divided as follows. Section 2 discusses the BLPMDC motor, and Section 3 is for the speed control of the motor. Moreover, the simulation model of both the motor and its drive is described in Section 4.

II. BRUSHLESS PERMANENT MAGNET DIRECT CURRENT (BLPMDC) MOTORS

BLPMDC motors have been of interest since the introduction of high-energy rare earth permanent magnet materials. This is because of the fact that such materials offer high flux density. The BLPMDC motor is a synchronous PM motor, which is driven by DC voltage through electrical power devices. It can be designed with a single-phase, two-phase, or three-phase motor. The rotor of the BLPMDC motor has no windings on it, instated it has permanent material on its surface (surface mounted permanent magnet motor) or buried inside its iron (interior permanent magnet motor), while the stator is being the same as that of the conventional Dc motor [31-36]. The BLPMDC motor is being replaced by the conventional DC motor in many applications due to the following advantages over the conventional DC motor:

Simple rotor configuration, no windings, no commutator. The absence of the brush allows for high-speed performance at both no-load and load conditions.

- High efficiency, no copper loss in the rotor.
- Lower electromagnetic interference.
- No mechanical commutator and consequently all its problems are eliminated.
- Less maintenance, less noise.
- Higher dynamic profile.
- Its torque/weight ratio is higher.
- Better torque-speed curve.

Developed torque in the BLPMDC motor is affected by the shape of the motor back-EMF waveform. Generally, the BLPMDC motor delivers back-EMF with a trapezoidal waveform, and the stator windings are usually fed by rectangular current waveforms. Hence, theoretically, the motor will deliver constant torque. However, due to the imperfection of the back-EMF waveform shape, the ripple of the current, and the commutation of the phase current, the torque ripple would be presented [37-42].

The mathematical model of a three-phase BLPMDC motor can be represented by Equations (1-8).

$$v_a = Ri_a + L\frac{di_a}{dt} + e_a \tag{1}$$

$$v_b = Ri_b + L\frac{di_b}{dt} + e_b \tag{2}$$

$$v_c = Ri_c + L\frac{di_c}{dt} + e_c \tag{3}$$

where v_a, v_b, v_c, i_a, i_b, and i_c are terminal voltage and input current of phases a, b, and c, receptivity, While R represents the resistance of the stator windings, which is equal for all phases for a balanced windings motor. Furthermore, L indicts induction of the stator windings, which is equal for all phases for a balanced windings motor. On the other hand, the back emf of phases a, b, and c is represented by e_a, e_b and e_c, respectively. The back-emf equations are given by

$$e_a(t) = k_e * \emptyset(\theta) * \omega(t) \tag{4}$$

$$e_b(t) = k_e * \emptyset(\theta - 120^o) * \omega(t) \tag{5}$$

$$e_c(t) = k_e * \emptyset(\theta + 120^o) * \omega(t) \tag{6}$$

where k_e is the back-EMF constant, $\emptyset$ is the flux, θ is the rotor angle in electrical degrees, and ω is the motor speed.

The developed electromagnetic torque (T_e) is given by following

$$T_e = \frac{(i_a * e_a) + (i_b * e_b) + (i_c * e_c)}{\omega} \tag{7}$$

On the other hand, the shaft torque is

$$T_e - T_L = B\omega + J\frac{d\omega}{dt} \tag{8}$$

where T_L represents load torque, B is the constant of the friction, and J is the rotor shaft inertia [27-32].

III. SPEED CONTROL OF BLPMDC MOTOR

Developing motor drives having high performance has become essential in all applications, from industrial to household applications. The BLPMDC motors are preferable to the conventional DC motors, as they have an electrical commentator and require less maintenance. However, BLPMDC motor drive systems suffer from the problem of high overshoot, which negatively affects drive performance. Hence, in order to ensure the requirement of all applications, the drive system of these motors must be efficient and has the features of high response, minimum overshoot as well as steady state error [33-35]. It was confirmed that the drive system of the electric motor could be enhanced by adopting the technique of Fuzzy Logic[36-39]. It leads to improve dynamic performance of the drive system and reduces the impact of load variations. It is capable of dealing with the system's nonlinearity without the needing for its mathematical model [40-42]. Due to its individuality features, such a controller is becoming popular and widely used in many sectors [43-47]. The structure of the Fuzzy logic controller is comprised of the following stages, Fuzzification, Knowledge, Fuzzy inference, and De-Fuzzification.

IV. THE SIMULATION DRIVE SYSTEM OF THE BLPMDC MOTOR

In this section, a simulation model of the BLPMDC motor and its speed control is discussed. The transfer function of the motor is given by Equation (9) [48]. The simulation model of the BLPMDC motor shows in Fig. 1.

$$T.F = \frac{K_T}{L_a J s^2 + (r_a J + L_a B_v)s + (r_a B_v + K_e K_T)} \tag{9}$$

$$T.F = \frac{4787}{s^2 + 132.8s + 1538} \tag{10}$$

It should be mentioned that three models have been simulated, including the BLPMDC motor without a controller, the BLPMDC motor with a PID controller, and BLPMDC with Fuzzy logic controller (FLC) [49, 50]. Fig. 1 shows the model of the BLPMDC motor without a controller built by T. F. on the other hand, Fig. 2 shows the model of the BLPMDC motor with PID controller, while the BLPMDC motor with FLC controller is displayed in Fig. 3. Fig. 4 shows the simulation models of BLPMDC motor without a controller, BLPMDC motor with PID controller and BLPMDC motor with FLC. On the other hand, Figs. 5 and 6 display the PID and the FL controller, respectively. Figs. 7-11 is Fuzzy Design.

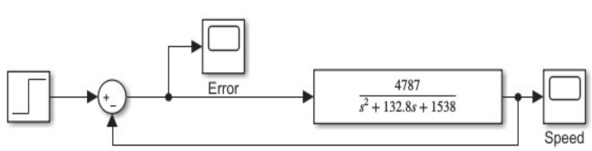


Fig. 1. Model of BLPMDC motor without controller

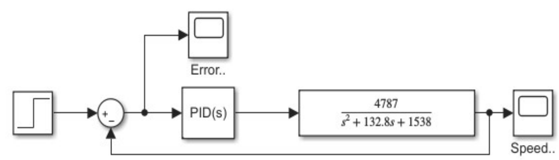


Fig. 2. Model of BLPMDC motor with PID controller

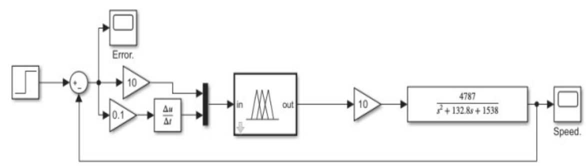


Fig. 3. Model of BLPMDC motor with FLC

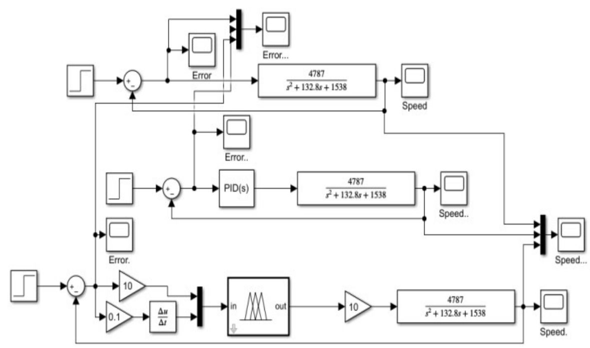


Fig. 4. Model of BLPMDC motor without a controller, with PID controller, and with FLC

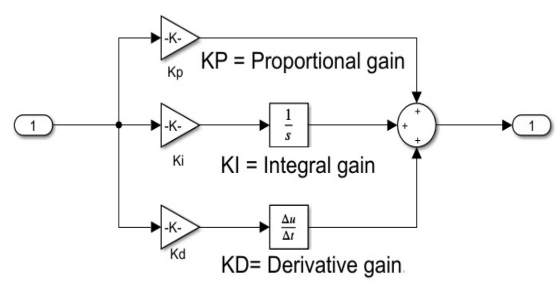


Fig. 5. PID controller

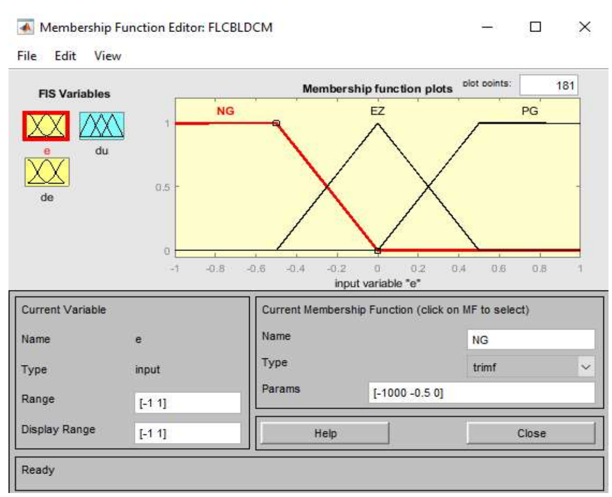


Fig. 6. FLC-Error-first input

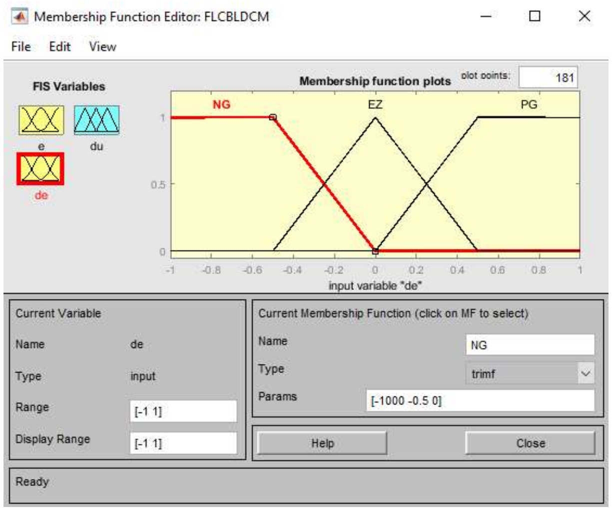


Fig. 7. FLC-Change of Error-2nd input

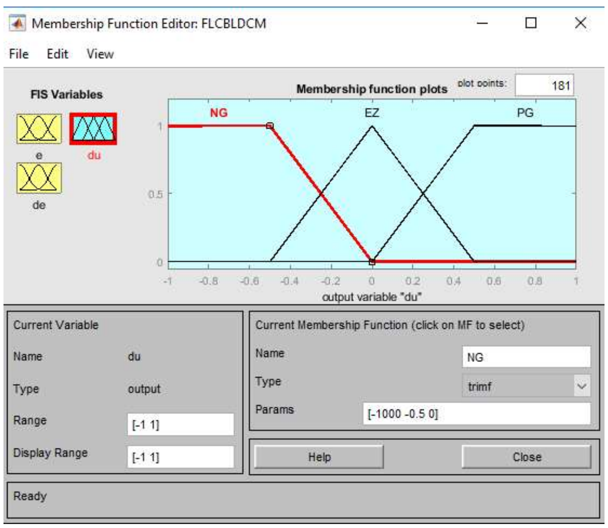


Fig. 8. FLC-Change of Error-3rd output

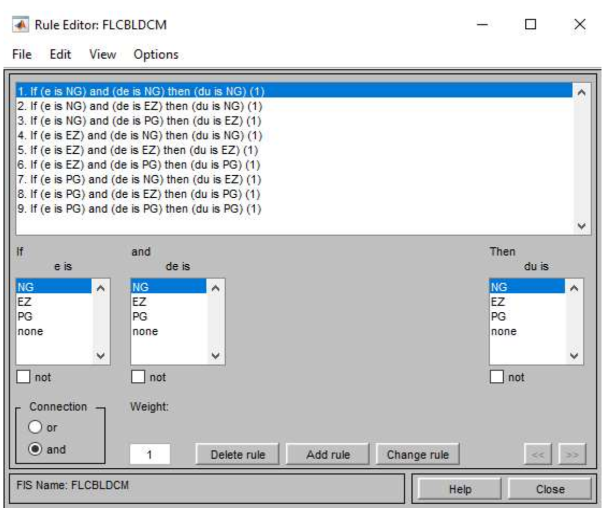


Fig. 9. FLC-Rule Editor of input (e, de) & output (du)

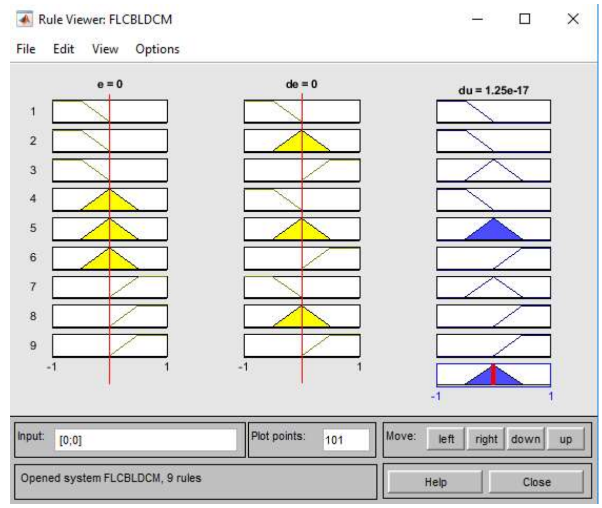


Fig. 10. FLC-Rule viewer of input(e,de) &output(du)

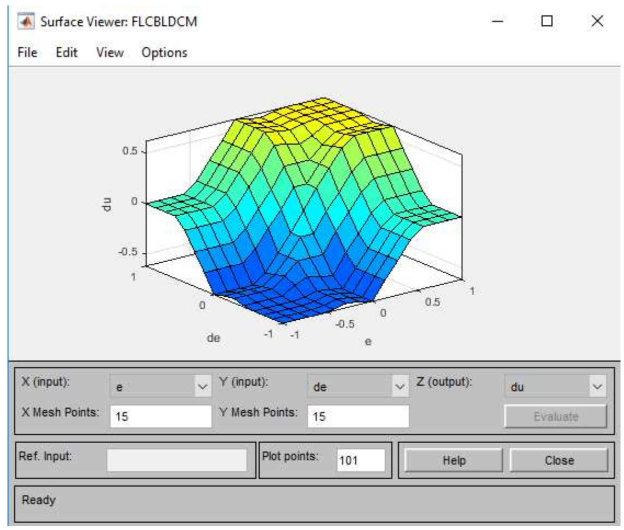
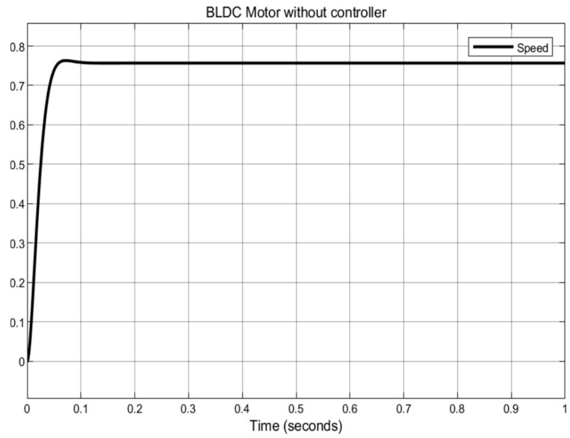


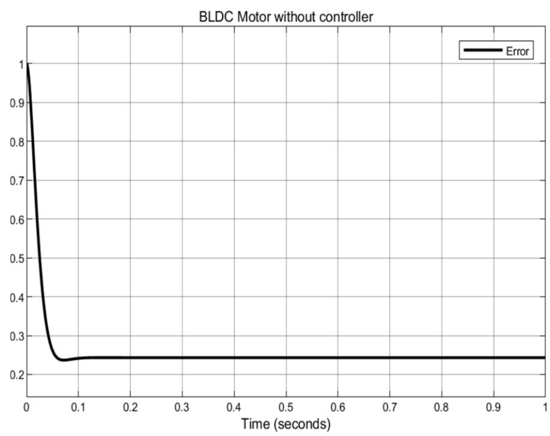
Fig. 11. The FLC-Surface viewer of input (e, de) & output (du)

V. Results And Discussion

In order to evaluate the proposed Fuzzy logic controller, three cases have been simulated, and the results were obtained for both speed and error. Fig. 12 (a and b) represent the response of speed and error, respectively, in the case of the motor without a controller, while Fig. 13 (a and b) display the simulation results for both speed and error responses, respectively, in the case of the PID controller. In addition, the response of both speed and error in the case of the proposed Fuzzy controller are shown in Fig. 14 (a and b), respectively. On the other hand, Fig. 15 (a) compares the speed responses for all three mentioned cases, and their error responses are compared in Fig. 15 (b). Apparently, less rise time, as well as overshoot, are delivered by the Fuzzy logic controller compared to the conventional (PID) counterpart. Table 1 summarizes the performances of both proposed and conventional controllers in terms of rise time, overshoot, and undershoot. The proposed controller offers about 70.5% less rise time and about 78% less overshoot compared to the conventional controller. However, in terms of undershooting, the proposed controller has about 85% higher value than the conventional one.

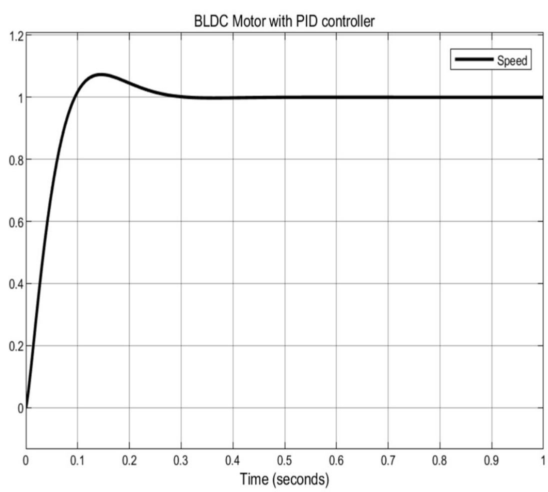


a. Speed

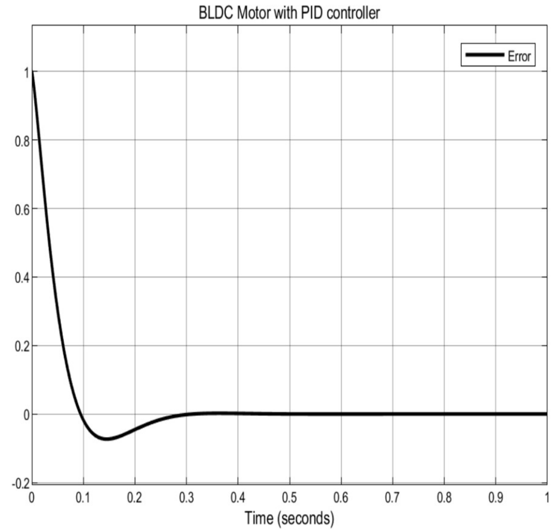


b. Error

Fig. 12. Simulation response of the motor without control

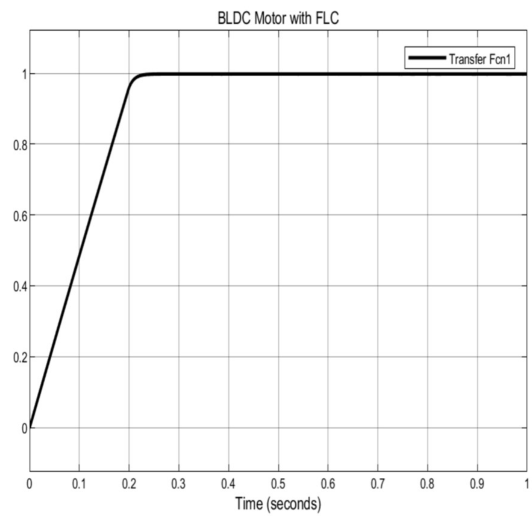


a. Speed

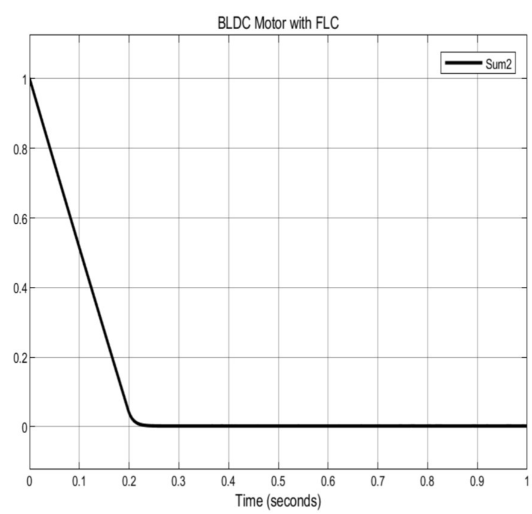


b. Error

Fig. 13. Simulation response of the motor with PID control

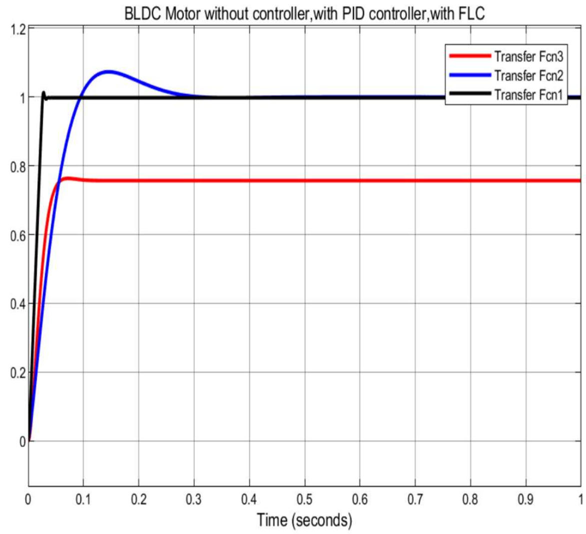


a. Speed

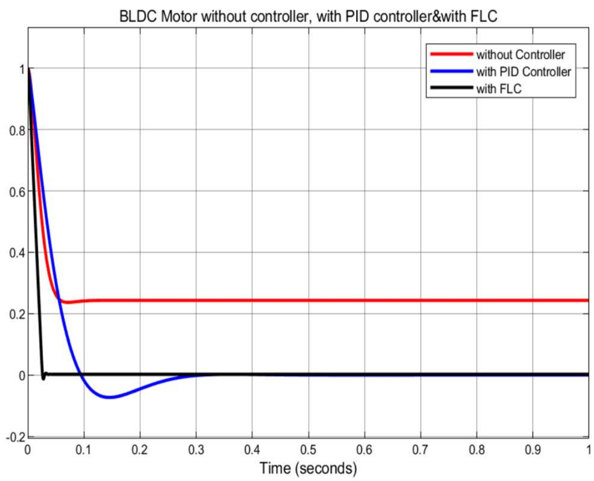


b. Error

Fig. 14. Simulation response of the motor with FLC



a. Speed



b. Error

Fig. 15. Simulation response of the motor without the controller, with PID controller, and with FLC

TABLE I. THE PERFORMANCE OF THE PID CONTROLLER AND FLC

Variable	PID	FLC
Rise Time (tr)	66.306ms	19.530ms
Overshoot	6.989%	1.531%
Undershoot	1.788%	11.924%

VI. CONCLUSION

The speed profile of an electric motor could be considered a vital parameter in many applications. In this paper, three simulation models of BLPMDC motors have been carried out in order to assess the performance of such motors in terms of speed and error responses. These three cases are the BLPMDC motor without the controller, the BLPMDC motor with the PID controller, and the BLPMDC motor with the FL controller. The results demonstrated that potential improvement of the motor performances would be obtained using either PID or FL controllers. However, the FC controller shows superior results compared to the PID controller in terms of less time rise as well as overshoot. The difference between both controllers was about 70% less rising time and about 78% less overshooting for the FC controller.

REFERENCES

[1] A. Ma'arif and N. R. Setiawan, "Control of DC motor using integral state feedback and comparison with PID: simulation and arduino implementation," *Journal of Robotics and Control (JRC),* vol. 2, no. 5, pp. 456-461, 2021.

[2] M. Khalifa, AL H. Amhedb, and M. Al Sharqawi, "Position Control of Real Time DC Motor Using LabVIEW," *Journal of Robotics and Control (JRC)*, vol. 2, no. 5, pp. 342-348, 2021.

[3] A. Ma'arif and A. Çakan, "Simulation and arduino hardware implementation of dc motor control using sliding mode controller," *Journal of Robotics and Control (JRC)*, vol. 2, no. 6, pp. 582-587, 2021.

[4] R. T. Yunardi, D. Arifianto, F. Bachtiar, and J. I. Prananingrum, "Holonomic implementation of three wheels omnidirectional mobile robot using dc motors," *Journal of Robotics and Control (JRC)*, vol. 2, no. 2, pp. 65-71, 2021.

[5] Y. I. Al Mashhadany, "High-performance multilevel inverter drive of brushless DC motor," *International Journal of Sustainable and Green Energy*, vol. 4, no. 3-1, pp. 1-7, 2015.

[6] S. W. Shneen, D. H. Shaker, and F. N. Abdullah, "Simulation model of PID for DC-DC converter by using MATLAB," *International Journal of Electrical and Computer Engineering*, vol. 11, no. 5, p. 3791, 2021.

[7] R. M. Pindoriya, et al., "Comparative analysis of permanent magnet motors and switched reluctance motors capabilities for electric and hybrid electric vehicles," *2018 IEEMA Engineer Infinite Conference (eTechNxT). IEEE*, pp. 1-5, 2018.

[8] A. E. Aliasand, and F. T. Josh, "Selection of motor foran electric vehicle: A review," *Materials Today: Proceedings*, vol. 24, pp. 1804-1815, 2020.

[9] N. Milivojevic, et al., "Stability analysis of FPGA-based control of brushless DC motors and generators using digital PWM technique," *IEEE transactions on industrial electronics*, vol. 59, no. 1, pp. 343-351, 2011.

[10] S. Hans, and S. Ghosh, "Position analysis of brushless direct current motor using robust fixed order H-infinity controller," *Assembly Automation*, vol. 40, no. 2, pp. 211-218, 2020.

[11] V. Madonna, et al., "The rebirth of the current source inverter: Advantages for aerospace motor design," *IEEE Industrial Electronics Magazine,* vol. 13, no. 4, pp. 65-76, 2019.

[12] D. H. Shaker, S. W. Shneen, F. N. Abdullah, and G. A. Aziz, "Simulation Model of Single-Phase AC-AC Converter by Using MATLAB," *Journal of Robotics and Control (JRC)*, vol. 3, no. 5, pp. 656-665, 2022.

[13] X. Ding, Y. Zhou, and J. Cheng, "A review of gallium nitride power device and its applications in motor drive," *CES Transactions on Electrical Machines and Systems,* vol. 3, no. 1, pp. 54-64, 2019.

[14] M. Galea et al., "Reliability-Oriented Design of Electrical Machines: The Design Process for Machines' Insulation Systems MUST Evolve," *IEEE Industrial Electronics Magazine*, vol. 14, no.1, pp. 20-28, 2020.

[15] X. F. Zheng, et al., "A review of thermoelectrics research–Recent developments and potentials for sustainable and renewable energy applications," *Renewable and Sustainable Energy Reviews,* vol. 32, pp. 486-503, 2014.

[16] J. C. Najmon, S. Raeisi, and A. Tovar, "Review of additive manufacturing technologies and applications in the aerospace industry," *Additive manufacturing for the aerospace industry*, pp. 7-31, 2019.

[17] H. S. Dakheel, Z. B. Abdullah, N. S. Jasim, and S. W. Shneen, "Simulation model of ANN and PID controller for direct current servo motor by using Matlab/Simulink," *Telkomnika*, vol. 20, no. 4, 2022.

[18] J. Feng, K. Liu, and Q. Wang, "Scheme based on buck-converter with three-phase H-bridge combinations for high-speed BLDC motors in aerospace applications," *IET Electric Power Applications*, vol. 12, no. 3, pp. 405-414, 2018.

[19] W. Chen et al., "A novel method of reducing commutation torque ripple for brushless DC motor based on Cuk converter," *IEEE Transactions on Power Electronics,* vol. 32, no. 7, pp. 5497-5508, 2016.

[20] X. Zhou et al. "Fast commutation instant shift correction method for sensorless coreless BLDC motor based on terminal voltage information," *IEEE Transactions on Power Electronics*, vol. 32, no. 12, pp. 9460-9472, 2017.

[21] H. A. Toliyat and T. Gopalarathnam, "AC machines controlled as DC machines (Brushless DC machines/electronics)," *The power electronics handbook, CRC Press*, 2018.

[22] S. W. Shneen, F. N. Abdullah, and D. H. Shaker, "Simulation model of single phase PWM inverter by using MATLAB/Simulink," *International Journal of Power Electronics and Drive Systems,* vol. 12, no. 1, p. 212, 2021.

[23] X. Xiang, J. Chai, and X. Sun, "A novel DC motor based on mechanical–electrical hybrid commutation," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 6, no. 3, pp. 1605-1615, 2017.

[24] R. Ramachandran, D. Ganeshaperumal and B. Subathra, "Closed-loop Control of BLDC Motor in Electric Vehicle Applications," *2019 IEEE International Conference on Clean Energy and Energy Efficient Electronics Circuit for Sustainable Development (INCCES),* pp. 1-5, 2019.

[25] B. Alsayid, W. A. Salah, and Y. Alawneh, "Modelling of sensored speed control of BLDC motor using MATLAB/SIMULINK," *International Journal of Electrical and Computer Engineering,* vol. 9, no. 5, pp. 3333-3343, 2019.

[26] A. A. El-Samahy and M. A. Shamseldin, "Brushless DC motor tracking control using self-tuning fuzzy PID control and model reference adaptive control," *Ain Shams Engineering Journal*, vol. 9, no. 3, pp. 341-352, 2018.

[27] S. W. Shneen, et al., "Application of LFAC {16 2/3Hz} for electrical power transmission system: a comparative simulation study," *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, vol. 17, no. 2, pp. 1055-1064, 2019.

[28] A. Azarudeen and D. Mary, "Performance analysis of conventional and digital PWM control scheme for speed control of BLDC motor drives," *2017 International Conference on Advances in Electrical Technology for Green Energy (ICAETGT),* pp. 69-75, 2017.

[29] K. S. Devi, R. Dhanasekaran and S. Muthulakshmi, "Improvement of speed control performance in BLDC motor using fuzzy PID controller," *2016 International Conference on Advanced Communication Control and Computing Technologies (ICACCCT),* pp. 380-384, 2016.

[30] M. A. Shamseldin and A. A. EL-Samahy, "Speed control of BLDC motor by using PID control and self-tuning fuzzy PID controller," *15th International Workshop on Research and Education in Mechatronics (REM),* pp. 1-9, 2014.

[31] A. J. Varghese, R. Roy and S. Thirunavukkarasu, "Optimized Speed Control for BLDC Motor," *International Journal of Innovative Research in Science Engineering and Technology,* vol. 3, pp. 1019 - 1030, 2014.

[32] H. H. Lwin and N. M. Seng, "Performance Comparison of P and PI Controller for Speed Control of Three Phase Brushless DC Motor," *International Journal of Trend in Research and Development,* vol. 5, no. 5, pp. 358-360, 2018.

[33] S. W. Shneen, H. S. Dakheel, and Z. B. Abdulla, "Design and implementation of variable and constant load for induction motor," *International Journal of Power Electronics and Drive Systems*, vol. 11, no. 2, p. 762, 2020.

[34] N. Leena and R. Shanmugasundaram, "Artificial neural network controller for improved performance of brushless DC motor," *2014 International Conference on Power Signals Control and Computations (EPSCICON),* pp. 1-6, 2014.

[35] S. Usha, P. M. Dubey, R. Ramya, and M.V. Suganyadevi, "Performance enhancement of BLDC motor using PID controller," *International Journal of Power Electronics and Drive Systems (IJPEDS),* vol. 12, no. 3, pp. 1335-1344, 2021.

[36] S. Mitra, R. S. Nayak, and R. Prakash," Modeling and Simulation of BLDC Motor using MATLAB/SIMULINK Environment," *International Research Journal of Engineering and Technology (IRJET),* vol. 2, no. 8, pp. 199-203, 2015.

[37] S. W. Shneen, C. Mao, and N. K. Bachache. "Biogeography based optimization for tuning FLC controller of PMSM," *International Conference in Swarm Intelligence. Springer, Cham,* pp. 395-402, 2015.

[38] B. N. Kommula and V. R. Kota, "Direct instantaneous torque control of Brushless DC motor using firefly Algorithm based fractional order PID controller," *Journal of King Saud University-Engineering Sciences*, vol. 32, no. 2, pp. 133-140, 2020.

[39] J. Karthikeyan and R. Dhanasekaran, "Resonant DC Link Inverter for Brushless DC Motor Drive System," *International Journal of Emerging Electric Power Systems,* vol. 13, no. 2, pp. 1-15, 2012.

[40] M. Kaur, A. Nehra, A. Tomar, and N. Charaya, "Speed Control of DC Motor using Artificial Intelligence," *International Journal for Research in Applied Science and Engineering Technology*, vol. 7, no. 6, pp. 913-917, 2019.

[41] W. Elsrogy, M. A. Fkirin, and M. M. Hassan, "Speed control of DC motor using PID controller based on artificial intelligence techniques," *2013 International Conference on Control, Decision and Information Technologies,* pp. 196-201, 2013.

[42] M. Alhanjouri, "Speed Control of DC Motor using Artificial Neural Network," *International Journal of Science and Research (IJSR)*, vol. 6, no. 2, pp. 2140 - 2148, 2017.

[43] S. A. Hamoodi, I. I. Sheet and R. A. Mohammed, "A Comparison between PID controller and ANN controller for speed control of DC Motor," *2019 2nd International Conference on Electrical, Communication, Computer, Power and Control Engineering (ICECCPCE),* pp. 221-224, 2019.

[44] S. W. Shneen, and G. A. Aziz, "Simulation model of 3-phase PWM rectifier by using MATLAB/Simulink," *International Journal of Electrical and Computer Engineering*, vol. 11, no. 5, p. 3736, 2021.

[45] R. Arulmozhiyal, "Design and Implementation of Fuzzy PID controller for BLDC motor using FPGA," *2012 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES),* pp. 1-6, 2012.

[46] N. Farouk and T. Bingqi, "Application of self-tuning fuzzy PID controller on the AVR system," *2012 IEEE International Conference on Mechatronics and Automation*, pp. 2510-2514, 2012.

[47] I. Anshory, I. Robandi, and Wirawan, "Parameters identification BLDC motor: Instrumentations and transfer functions," *MATEC Web of Conferences, EDP Sciences,* vol. 197, 2018.

[48] F. N. Abdullah, G. A. Aziz, and S. W. Shneen, "Simulation Model of Servo Motor by Using Matlab," *Journal of Robotics and Control (JRC),* vol. 3, no. 2, 176-179, 2022.

[49] D. Maneetham and P. Sutyasadi, "Controlling a knee CPM machine using PID and iterative learning control algorithm," *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, vol. 18, no. 2, pp. 1047-1053, 2022.

[50] A. Tikkani and P. V. N. Prasad, "Type-1 and type-2 fuzzy logic-based space vector modulation for two-level inverter fed induction motor," *Telkomnika*, vol. 20, no. 4, 2022.