



Speed Control of DC Motors Using PID and Fuzzy Logic Controllers: A Comparative Study

Deepansh Nithisarn

Department of Electrical and Computer Engineering, Kelana Technical and Management College, Malaysia
deepansh.nithisarn@ktmc-my.net

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Abstract

This methodology paper presents a reproducible comparative framework for evaluating proportional-integral-derivative (PID) and fuzzy logic controllers (FLCs) for the speed regulation of a separately excited direct-current (DC) motor. A common electromechanical motor model, identical voltage saturation, the same reference speed, and the same external load disturbance are used so that differences in response arise from the control strategy rather than from unequal test conditions. The PID controller is tuned for a stable compromise between rise time, overshoot, settling time, and steady-state error. The fuzzy controller uses speed error and error derivative as inputs, five linguistic terms per input, a 25-rule Mamdani-type rule base, and centroid-style weighted defuzzification. MATLAB/Simulink is the intended implementation environment; the numerical results reported here were reproduced from the stated differential equations using an equivalent time-domain simulation. For a 150 rad/s command, the PID response reaches the target faster initially, but exhibits about 6.20% overshoot and settles in approximately 0.596 s. The fuzzy controller reduces overshoot to about 0.64% and settles in about 0.300 s, although its non-integrating rule structure leaves a small post-disturbance speed offset of about 0.93%. The comparison therefore indicates that fuzzy logic provides superior transient damping and smoothness, while PID retains an advantage in eliminating constant steady-state error when integral action is properly tuned. The methodology can be used as a baseline for later hardware-in-the-loop or laboratory validation.

Introduction

DC motors remain important in variable-speed industrial drives, positioning systems, robotic actuators, conveyors, laboratory servos, and low-power automation because their torque and speed can be regulated conveniently through armature voltage. The control problem is nevertheless nontrivial when load torque changes, actuator limits are present, and motor parameters vary. Classical PID control is still widely used because of its transparent structure and practical tuning rules; its continuing industrial relevance and limitations have been

extensively discussed in the control literature [3]. Design methods can explicitly relate PI/PID parameters to transient-response specifications, providing a systematic alternative to purely trial-and-error adjustment [4].

Fuzzy logic offers a different control philosophy. The fuzzy-set framework introduced by Zadeh [1] allows degrees of membership instead of binary classification, while the linguistic-controller concept demonstrated by Mamdani and Assilian [2] converts heuristic operator knowledge into rules. In motor control, this is

attractive because a rule base can react differently to large, small, increasing, or decreasing speed errors without requiring one fixed linear gain over the entire operating region. Earlier DC-motor studies reported good transient behaviour from fuzzy control and intelligent tuning methods [5]-[12].

The objective of this paper is therefore to define and demonstrate a fair methodology for comparing a conventional PID controller with a fuzzy logic controller on the same DC motor. The comparison focuses on rise time, settling time, overshoot, steady-state accuracy, response to a step load disturbance, integral absolute error (IAE), and control effort. All references are restricted to publications from 2015 or earlier, as required.

Literature Review

The theoretical basis of fuzzy control originates in Zadeh's formulation of fuzzy sets [1]. Mamdani and Assilian subsequently demonstrated how linguistic IF-THEN rules could synthesize a practical controller without reducing the entire decision process to a single linear equation [2]. In parallel, PID control developed into the dominant general-purpose feedback architecture because proportional action improves responsiveness, integral action removes steady-state offset, and derivative action can improve damping when noise is managed appropriately [3]. Basilio and Matos [4] showed how controller parameters may be selected to satisfy transient-performance requirements, which is directly relevant when motor controllers are judged by overshoot and settling time.

Research specifically addressing DC-motor speed regulation increasingly compared conventional and intelligent controllers before 2015. Rai,

Singhal, and Nandwani [5] applied fuzzy logic to DC-motor speed control and emphasized the ability of the rule-based scheme to handle nonlinear behaviour. Bouall  gue et al. [6] proposed particle-swarm-based tuning for PID-type fuzzy logic control, illustrating that fuzzy-controller scaling and parameters can be optimized rather than selected only by intuition. Sadiq et al. [7] used fuzzy controllers with combined armature-voltage and field-current regulation, demonstrating the flexibility of fuzzy logic across operating regions. Panicker and Mol [8] reported hybrid PI-fuzzy speed control for a brushless DC motor, representing the broader trend toward combining the zero-error property of integral action with fuzzy transient adaptation.

Optimization and self-tuning studies further clarified the trade-offs. Mishra et al. [9] used artificial bee colony optimization for DC-motor speed-control tuning. Nguyen and Komeda [10] optimized a fuzzy controller for a DC servomotor using motor-speed profiles and a genetic algorithm and reported improved dynamic response relative to a conventional PID benchmark. Sabir and Khan [11] optimized PID parameters for DC-motor speed control using metaheuristic techniques, confirming that PID performance is highly sensitive to gain selection. Akbari-Hasanjani et al. [12] proposed a self-tuning fuzzy PID algorithm in which the effective gains vary with operating error, specifically targeting overshoot and settling time. Fereidouni et al. [13] also developed an adaptive PID-type fuzzy configuration, reinforcing the value of variable controller behaviour when a single fixed set of gains is insufficient. Adepoju et al. [14] provided an additional application of fuzzy logic to the speed control of a separately excited DC motor and reported satisfactory simulated tracking.

Table 1. Summary of literature directly informing the comparative methodology.

Ref.	Year	Main method	Relevance to this study
[3]	2001	PID review	Establishes PID strengths, limitations, and continuing practical role.
[5]	2012	Fuzzy DC-motor control	Shows direct application of FLC to motor-speed regulation.
[6]	2012	PSO-tuned fuzzy PID	Highlights importance of systematic fuzzy/PID tuning.
[7]	2013	Fuzzy armature/field control	Demonstrates rule-based control over DC-motor operating regions.
[10]	2014	GA-optimized FLC	Reports improved servomotor dynamic performance over PID.
[11]	2014	Metaheuristic PID	Shows that PID outcome depends strongly on gain optimization.
[12]	2015	Self-tuning fuzzy PID	Targets lower overshoot and shorter settling time.
[13]	2015	Adaptive PID-type FLC	Supports variable-gain intelligent control under changing conditions.

Research gap and methodological position: much of the earlier literature demonstrates either one controller, a hybrid controller, or an optimized controller. The present study instead emphasizes a controlled comparison: the plant model, reference, actuator saturation, sampling interval, simulation duration, and disturbance are held constant. The PID and FLC are then judged using the same quantitative performance indicators. This design isolates controller behaviour and makes the interpretation of advantages and disadvantages more transparent.

Methodology

1. Research Design and Test Conditions

A comparative simulation design is used. Two closed-loop systems are created around the same

separately excited DC-motor plant: System A uses PID control and System B uses fuzzy logic control. Only the controller block is changed. Both systems use a 24 V armature-voltage limit, an initial speed command of 0 rad/s, a step to 150 rad/s at $t = 0.1$ s, and a 0.05 N·m load-torque disturbance applied at $t = 1.5$ s. The total simulated interval is 3 s. The numerical integration step is 0.0002 s; in a Simulink implementation, a sufficiently small fixed or variable solver step should be selected so that controller and electrical dynamics are accurately resolved.

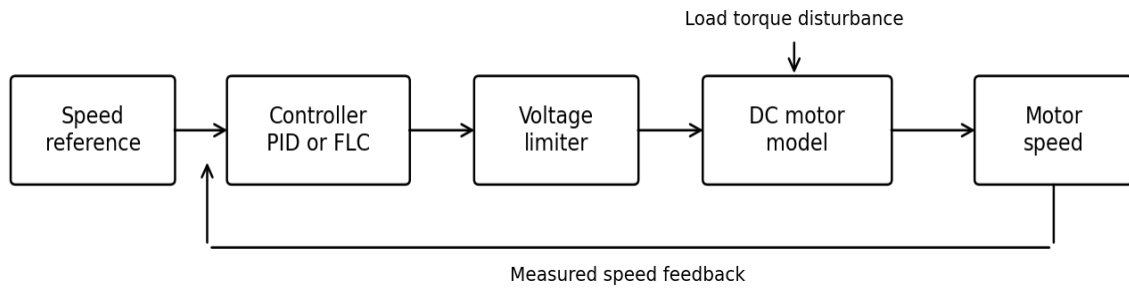


Figure 1. Common closed-loop architecture used for the PID and fuzzy-controller tests.

2. Mathematical Model of the DC Motor

The armature-controlled motor is represented by the standard electrical and mechanical equations. The back electromotive force is proportional to angular speed and the electromagnetic torque is proportional to armature current. The governing equations are:

$$V_a = L_a(di_a/dt) + R_a i_a + K_e \omega$$

$$J(d\omega/dt) + B\omega = K_t i_a - T_l$$

where V_a is armature voltage, i_a is armature current, R_a and L_a are armature resistance and inductance, J is rotor-load inertia, B is viscous friction, K_e is the back-EMF constant, K_t is the torque constant, ω is angular speed, and T_l is load torque. With $K_e = K_t = K$ in SI units, the no-load transfer function from armature voltage to speed is:

$$\Omega(s)/V_a(s) = K / [(L_a s + R_a)(J s + B) + K^2]$$

Table 2. DC-motor and actuator parameters used in the common plant model.

Parameter	Symbol	Value	Unit
Armature resistance	R_a	1.0	Ω
Armature inductance	L_a	0.05	H
Torque/back-EMF constant	$K_t = K_e$	0.10	N·m/A; V·s/rad
Equivalent inertia	J	0.002	kg·m ²
Viscous friction	B	0.001	N·m·s/rad
Voltage saturation	V_{max}	± 24	V

These values define a stable low-voltage motor model suitable for a transparent controller comparison. They are not presented as measurements from a particular commercial motor. For experimental replication, the same procedure can be used after replacing Table 2

with identified motor parameters obtained from datasheets or laboratory tests.

3. PID Controller Design

The PID controller operates on speed error $e(t) = \omega_{ref}(t) - \omega(t)$. Its command is $u_{PID}(t) = K_p e(t) + K_i \int e(t) dt + K_d de(t)/dt$. A practical output

saturation of ± 24 V is applied. Conditional integration is used as a simple anti-windup mechanism: the integral state is not allowed to accumulate further when the actuator is saturated in a direction that would increase saturation. The gains used for the baseline comparison are $K_p = 0.20$, $K_i = 2.00$, and $K_d = 0.001$. These gains were selected iteratively to produce a stable, reasonably fast response without excessive oscillation. This tuning philosophy is consistent with the need to balance transient measures in classical PID design [3], [4], while optimization-based work shows that alternative gain searches can further improve performance [9], [11].

4. Fuzzy Logic Controller Design

The fuzzy controller uses two normalized inputs: speed error e and error derivative de/dt . Each input has five triangular/shoulder linguistic

membership functions: Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB). The error range is normalized using a scale of 40 rad/s and the derivative range using 1000 rad/s². The output is a normalized voltage correction with five corresponding linguistic levels. A no-load model bias supplies the approximate voltage needed to maintain the commanded speed, and fuzzy inference adds or subtracts up to 10 V according to the instantaneous error state. This structure allows strong action for large errors and softer action near the set point. Mamdani-style minimum implication and weighted centroid singleton aggregation are used. The approach follows the rule-based philosophy established by fuzzy-control literature [1], [2] and motor applications [5], [7], [14].

Table 3. Five-by-five fuzzy rule base for the voltage-correction output.

$e \setminus d(e)/dt$	NB	NS	ZE	PS	PB
NB	NB	NB	NB	NS	ZE
NS	NB	NB	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PB	PB
PB	ZE	PS	PB	PB	PB

5. Evaluation Procedure

The following steps are used for both controllers: (1) initialize speed and armature current to zero; (2) apply the 150 rad/s speed command at 0.1 s; (3) record speed, error, and controller voltage; (4) apply 0.05 N·m load torque at 1.5 s; and (5) continue the simulation to 3 s. The response is assessed using 10–90% rise time, 2% settling

time before the load step, percent overshoot, pre-disturbance steady-state error, final post-disturbance error, IAE over the commanded interval, disturbance-induced speed dip, and RMS controller voltage. This common set of metrics prevents a controller from being judged only by the one characteristic in which it performs best.

Table 4. Performance measures used for the controller comparison.

Metric	Definition	Preferred direction
Rise time	Time from 10% to 90% of 150 rad/s	Lower
Settling time	Time to remain within $\pm 2\%$ before disturbance	Lower
Overshoot	$(\text{peak} - \text{reference})/\text{reference} \times 100\%$	Lower
Steady-state error	Absolute reference minus measured speed	Lower
IAE	$\int e(t) dt$ over the commanded interval	Lower
RMS voltage	Root-mean-square armature command	Lower, subject to performance

Results

Figure 2 presents the simulated speed responses using the common test conditions. Both controllers track the 150 rad/s command and remain stable. The PID controller initially rises slightly faster, but its integral action and fixed gains produce a larger transient peak. The fuzzy controller approaches the target more

progressively and suppresses the peak substantially. At $t = 1.5$ s, the load step reduces speed in both systems. PID integral action subsequently restores essentially zero final offset. The selected fuzzy structure has no dedicated integral state; consequently, it shows a small residual error under the constant load even though the disturbance-induced dip is modest.

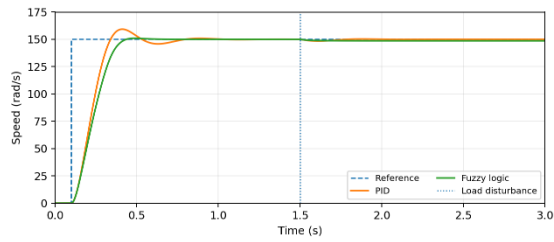


Figure 2. Simulated speed response of PID and fuzzy logic controllers; load torque is applied at 1.5 s.

Table 5. Quantitative comparison obtained from the stated simulation model and controller settings.

Performance measure	PID	Fuzzy logic	Better result
Rise time (s)	0.161	0.202	PID
Settling time (s)	0.596	0.300	Fuzzy
Overshoot (%)	6.20	0.64	Fuzzy
Pre-disturbance error (rad/s)	0.012	0.000	Fuzzy $\approx$ PID
Speed dip after load step (rad/s)	1.623	1.338	Fuzzy
Final error under constant load (rad/s)	0.000	1.389	PID
IAE (rad)	19.99	22.61	PID
RMS command voltage (V)	17.26	17.00	Fuzzy (slightly)

Comparative Interpretation

The PID controller achieves a rise time of 0.161 s, compared with 0.202 s for the FLC, so PID is about 20.4% faster by this specific 10–90% measure. However, its peak reaches approximately 159.3 rad/s, corresponding to 6.20% overshoot, whereas the fuzzy peak is about 151.0 rad/s or only 0.64% overshoot. Because of the reduced oscillatory transient, the fuzzy controller enters and remains within the 2% band at roughly 0.300 s, compared with 0.596 s for PID.

The disturbance comparison adds an important qualification. The PID speed dip is about 1.62 rad/s and the final error is essentially zero because integral action continues to correct a constant load. The fuzzy controller experiences a slightly smaller initial dip of about 1.34 rad/s, but its final speed is approximately 148.61 rad/s, leaving 1.39 rad/s (0.93%) error. Thus, the present FLC is superior for transient damping but not for perfect rejection of a persistent load. Earlier self-tuning and hybrid studies similarly motivate combining fuzzy adaptation with integral/PID mechanisms when both transient quality and zero offset are required [8], [12], [13].

Conclusion and Discussion

The comparative methodology demonstrates that the choice between PID and fuzzy logic should not be reduced to a single statement that one controller is universally superior. Under the same DC-motor model, actuator saturation, speed reference, and load disturbance, the two approaches display distinct strengths. The tuned PID controller produces the shortest 10–90%

rise time and, because it contains integral action, removes the steady-state error caused by a constant load. Its disadvantage in the present tuning is a noticeably larger overshoot and longer settling interval. The fuzzy controller uses nonlinear rule-based action to reduce control aggressiveness as the speed approaches its target. This produces a much smaller overshoot and a shorter 2% settling time, consistent with the motivation for intelligent motor controllers reported in earlier studies [5], [7], [10], [12], [14]. From a control-design perspective, the PID result confirms why this controller remains a dependable industrial baseline. It is compact, easy to implement on low-cost microcontrollers, and its parameters have a clear physical effect on response. When the plant is reasonably well modeled and operating conditions do not vary drastically, a carefully tuned PID can provide excellent tracking. The same simplicity can become a weakness, however, because one fixed set of gains must compromise between fast rise, low overshoot, noise sensitivity, and disturbance rejection. Optimization-based tuning can improve this compromise [9], [11], but the gains are still fixed unless an adaptive mechanism is added. The fuzzy controller requires additional design choices: input/output scaling factors, membership-function shapes, rule-base structure, inference method, and defuzzification. These choices can be guided by engineering knowledge and later optimized, as shown in fuzzy-controller tuning research [6], [10]. Its principal advantage is nonlinear gain-like behaviour: large errors can trigger strong corrective voltage, while near-zero errors can trigger smaller actions that reduce overshoot. In the present implementation this produces better

transient damping. The observed residual load error also illustrates an important limitation. A fuzzy PD-like structure does not automatically guarantee zero steady-state error. Designers who require both rapid damping and exact rejection of constant disturbances should consider a fuzzy PI structure, a fuzzy self-tuning PID controller, or an explicit integral rule mechanism, as supported by the hybrid/adaptive literature [8], [12], [13].

Practical Implications

- Use a conventional PID controller when low implementation cost, transparent tuning, and zero steady-state error under constant disturbances are the primary requirements.
- Use an FLC when nonlinear response shaping, low overshoot, smoother transients, and tolerance to uncertain operating behaviour are more important than minimum algorithmic complexity.
- For demanding drives, combine fuzzy adaptation with PI/PID action so that transient nonlinearity and integral disturbance rejection are both available.
- Keep plant conditions identical during comparative tests; otherwise, apparent controller superiority may result from unequal saturation, sampling, filters, or disturbances rather than the control method itself.

Limitations and Future Work

The present study is simulation-based and uses a nominal linear electromechanical model with voltage saturation. It does not include brush voltage drop, Coulomb friction, dead-zone effects, encoder quantization, PWM switching ripple, supply variation, measurement noise, thermal resistance change, or computational delay. These nonidealities can alter controller ranking in hardware. Future work should therefore implement both controllers on the same microcontroller and motor drive, identify actual motor parameters, introduce repeatable load steps, and report averaged experimental results. Additional comparisons may include optimized PID, fuzzy PI, self-tuning fuzzy PID, and robustness tests under ± 10 – 20% parameter uncertainty. The methodology described here provides a controlled baseline for those extensions.

In conclusion, for the selected test case the FLC provides the better transient response, reducing overshoot from approximately 6.20% to 0.64% and settling time from about 0.596 s to 0.300 s. PID provides the better final accuracy under a sustained load because of integral action.

Therefore, the most defensible conclusion is not that fuzzy control replaces PID, but that fuzzy logic offers stronger nonlinear transient shaping, while PID offers simplicity and exact steady-state correction; hybrid fuzzy-PID structures are a logical next step when both properties are required.

References

- L. A. Zadeh, "Fuzzy sets," *Information and Control*, vol. 8, no. 3, pp. 338–353, 1965. DOI: 10.1016/S0019-9958(65)90241-X.
- E. H. Mamdani and S. Assilian, "An experiment in linguistic synthesis with a fuzzy logic controller," *International Journal of Man-Machine Studies*, vol. 7, no. 1, pp. 1–13, 1975. DOI: 10.1016/S0020-7373(75)80002-2.
- K. J. Åström and T. Hägglund, "The future of PID control," *Control Engineering Practice*, vol. 9, no. 11, pp. 1163–1175, 2001. DOI: 10.1016/S0967-0661(01)00062-4.
- J. C. Basilio and S. R. Matos, "Design of PI and PID controllers with transient performance specification," *IEEE Transactions on Education*, vol. 45, no. 4, pp. 364–370, 2002. DOI: 10.1109/TE.2002.804399.
- J. N. Rai, M. Singhal, and M. Nandwani, "Speed control of DC motor using fuzzy logic technique," *IOSR Journal of Electrical and Electronics Engineering*, vol. 3, no. 6, pp. 41–48, 2012. DOI: 10.9790/1676-0364148.
- S. Bouallège, J. Haggège, M. Ayadi, and M. Benrejeb, "PID-type fuzzy logic controller tuning based on particle swarm optimization," *Engineering Applications of Artificial Intelligence*, vol. 25, no. 3, pp. 484–493, 2012. DOI: 10.1016/j.engappai.2011.09.018.
- A. Sadiq, G. A. Bakare, E. C. Anene, and H. B. Mamman, "A fuzzy-based speed control of DC motor using combined armature voltage and field current," *IFAC Proceedings Volumes*, vol. 46, no. 20, pp. 387–392, 2013. DOI: 10.3182/20130902-3-CN-3020.00146.
- D. K. Panicker and M. R. Mol, "Hybrid PI-fuzzy controller for brushless DC motor speed control," *IOSR Journal of Electrical and Electronics Engineering*, vol. 8, no. 6, pp. 33–43, 2013. DOI: 10.9790/1676-0863343.
- K. Mishra, A. Khanna, N. K. Singh, and V. K. Mishra, "Speed control of DC motor using artificial bee

colony optimization technique," *Universal Journal of Electrical and Electronic Engineering*, vol. 1, no. 3, pp. 68–75, 2013. DOI: 10.13189/ujeee.2013.010302.

T. T. Nguyen and T. Komeda, "Using motor speed profile and genetic algorithm to optimize the fuzzy logic controller for controlling DC servomotor," *International Journal of Computer Applications*, vol. 94, no. 14, pp. 1–8, 2014. DOI: 10.5120/16408-6076.

M. M. Sabir and J. A. Khan, "Optimal design of PID controller for the speed control of DC motor by using metaheuristic techniques," *Advances in Artificial Neural Systems*, vol. 2014, Article 126317, pp. 1–8, 2014. DOI: 10.1155/2014/126317.

R. Akbari-Hasanjani, S. Javadi, and R. Sabbaghi-Nadooshan, "DC motor speed control by self-tuning fuzzy PID algorithm," *Transactions of the Institute of Measurement and Control*, vol. 37, no. 2, pp. 164–176, 2015. DOI: 10.1177/0142331214535619.

Fereidouni, M. A. S. Masoum, and M. Moghbel, "A new adaptive configuration of PID type fuzzy logic controller," *ISA Transactions*, vol. 56, pp. 222–240, 2015. DOI: 10.1016/j.isatra.2014.11.010.

G. A. Adepoju, I. A. Adeyemi, and O. S. Oni, "Application of fuzzy logic to the speed control of DC motor," *International Journal of Engineering Trends and Technology*, vol. 15, pp. 215–219, 2014. DOI: 10.14445/22315381/IJETT-V15P243.