



Comparative Study of PID and Fuzzy Logic Controllers for DC Motor Speed Control

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Abstract

Direct-current (DC) motors remain important in variable-speed drives because of their simple electromagnetic structure, high starting torque, and convenient armature-voltage control. Their speed regulation, however, is affected by load-torque disturbances, parameter variation, actuator saturation, and the trade-off between rapid response and overshoot. This paper presents a comparative simulation study of a conventional proportional-integral-derivative (PID) controller and a Mamdani-type fuzzy logic controller (FLC) for closed-loop DC motor speed control. A common armature-controlled motor model is used so that the two strategies are evaluated under identical electrical, mechanical, reference-speed, and disturbance conditions. The PID gains are selected to obtain a fast stable response, whereas the FLC uses speed error and change of error as linguistic inputs with seven membership levels. A 60 rad/s reference step and a 0.15 N.m load-torque step at 3 s are applied. Performance is assessed using rise time, 2% settling time, percentage overshoot, steady-state error, maximum disturbance deviation, recovery time, integral absolute error, and root-mean-square error. The simulation shows that PID produces the faster initial rise, while fuzzy control reduces overshoot, shortens settling time, virtually removes pre-disturbance steady-state error, and limits the speed dip after the load change. The results support fuzzy logic as an effective alternative when robustness and low transient deviation are prioritized, while PID remains attractive when simplicity, analytical tuning, and rapid initial acceleration are the principal requirements.

Introduction

DC motors are widely used in laboratory drives, robotics, conveyors, positioning systems, electric actuation, and low- to medium-power industrial applications. The main control objective is to maintain the commanded shaft speed despite changes in load torque and operating point. For an armature-controlled motor, the electrical and mechanical dynamics are coupled through back electromotive force and electromagnetic torque; consequently, a controller that is satisfactory at one operating point can exhibit overshoot, delayed recovery, or steady-state error when the

disturbance level changes. Classical DC-motor studies therefore emphasize closed-loop voltage regulation and careful controller selection [2].

The PID controller is one of the most common solutions because its proportional action reacts to present error, integral action removes persistent offset, and derivative action anticipates the error trend. Its advantages are a compact structure, low computational cost, and straightforward implementation in analog, microcontroller, PLC, or digital-signal-processing platforms. The major limitation is that fixed gains

represent a compromise. Aggressive gains can provide a short rise time but may amplify noise and increase overshoot; conservative gains reduce oscillation but slow down response and disturbance rejection. Changes in motor inertia, friction, supply voltage, or load can further shift the best tuning away from its nominal value.

Fuzzy logic provides a different control philosophy. Zadeh's fuzzy-set framework [1] permits numerical variables to be described by overlapping linguistic classes, enabling control rules such as "if error is positive large and error change is negative, reduce the command moderately." Instead of relying completely on an exact plant model, the FLC encodes qualitative knowledge through membership functions, a rule base, inference, and defuzzification. This feature has motivated extensive use of fuzzy and fuzzy-PID methods for DC and brushless DC drives [3]–[10].

The aim of this methodology paper is to compare PID and fuzzy logic controllers using the same DC-motor plant, voltage limit, speed command, and load disturbance. The study is deliberately simulation-based: it defines a reproducible mathematical model, controller parameters, fuzzy rule structure, performance metrics, and test sequence. The main research question is whether fuzzy control can reduce transient deviation and improve disturbance robustness without sacrificing acceptable response speed when compared with a well-behaved fixed-gain PID controller.

Literature Review

Early work on fuzzy sets established a mathematical basis for graded membership rather than binary classification [1]. This concept later became useful in control problems in which operating knowledge is easier to express linguistically than through a precise nonlinear model. In the DC-drive context, George [2] demonstrated the importance of closed-loop speed control for separately excited DC motors and provided a representative modeling basis for simulation-oriented evaluation.

Hamed and Almobaied [3] implemented fuzzy PID speed control for a DC motor using FPGA technology. Their work highlighted the suitability of fuzzy reasoning for real-time digital control and showed that high-speed hardware can execute the inference process with deterministic timing. Kandiban and Arulmozhiyal [4] compared conventional PID, fuzzy PID, and adaptive fuzzy PID approaches for a brushless DC motor. Their results indicated that adaptation of the control parameters can

improve transient behavior when motor dynamics and operating conditions vary.

Sadiq et al. [5] applied fuzzy logic to a separately excited DC motor using combined armature-voltage and field-current control. The study is relevant because it showed that fuzzy rules can coordinate more than one manipulated variable and can be used across constant-torque and constant-power regions. Ramadan et al. [6] further developed an improved adaptive fuzzy controller and implemented the method on FPGA hardware for DC motor speed control. Their work connected fuzzy design with practical embedded implementation and emphasized real-time performance.

Khater, El-Bardini, and El-Rabaie [7] introduced reinforcement-learning-based adaptation of fuzzy scaling factors for a flexible-shaft DC motor, reporting improved behavior over non-adaptive alternatives. The study illustrates a broader trend: fuzzy control can serve as a base structure whose scaling or rules are modified online to improve robustness. By 2016, fuzzy-PID approaches had become established enough for multiple BLDC studies. Devi et al. [8] reported improved speed-control performance using a fuzzy PID controller, while Davoudkhani and Akbari [9] compared an interval type-2 fuzzy PID approach with conventional PID and type-1 fuzzy PID controllers. Jing, Wang, and Huang [10] likewise investigated fuzzy-PID control for a BLDC motor.

Across these studies, the recurring conclusion is not that fuzzy control always dominates PID in every metric, but that fuzzy reasoning can reduce sensitivity to nonlinearities, uncertain operating conditions, and abrupt disturbances. A gap remains in many comparisons because controller structures, motor parameters, speed commands, and disturbance profiles differ from one study to another. The present methodology addresses this issue by holding the plant and test conditions constant and reporting several time-domain indicators for both controllers.

Methodology

1. DC Motor Mathematical Model

A separately excited armature-controlled DC motor is represented by the standard electrical and mechanical differential equations. The armature circuit is described by

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

and the rotor mechanical dynamics are

$$J (d\omega/dt) + b\omega(t) = K_t i_a(t) - T_L(t).$$

Here, V_a is armature voltage, i_a is armature current, ω is shaft speed, T_L is loading torque, R_a and L_a are armature resistance and inductance, J is rotor inertia, b is viscous-friction coefficient, and K_e and K_t are the back-EMF and

torque constants. The numerical values in Table 1 were selected to provide a stable low-power motor model with a 24 V actuator limit and a feasible 60 rad/s operating speed.

Table 1. DC motor and simulation parameters

Parameter	Symbol	Value	Unit
Armature resistance	R_a	1.0	Ω
Armature inductance	L_a	0.5	H
Torque constant	K_t	0.1	N·m/A
Back-EMF constant	K_e	0.1	V·s/rad
Rotor inertia	J	0.01	kg·m ²
Viscous friction	b	0.01	N·m·s/rad
Voltage saturation	V_{max}	± 24	V
Reference speed	ω_{ref}	60	rad/s
Load step at 3 s	T_L	0.15	N·m
Simulation time step	Δt	0.001	s

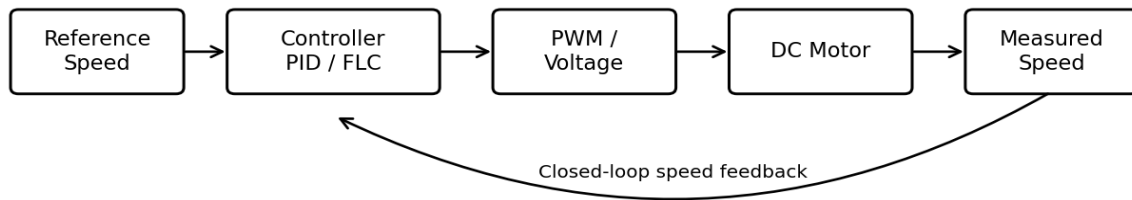


Figure 1. Common closed-loop architecture used for both controller tests.

2. PID Controller Design

The PID command is defined as $u(t) = K_p e(t) + K_i \int e(t) dt + K_d de(t)/dt$, where $e(t) = \omega_{ref}(t) - \omega(t)$. The gains used in the comparative test are $K_p = 2.0$, $K_i = 2.0$, and $K_d = 0.1$. The controller output is limited to ± 24 V. Conditional integration is used as a simple anti-windup measure: the integral state is not allowed to continue increasing when the voltage is saturated in the same direction as the speed error. These gains were chosen to give a fast and stable nominal response without excessive overshoot, providing a meaningful baseline rather than an intentionally poor PID tuning.

3. Fuzzy Logic Controller Design

The fuzzy controller is a Mamdani-style two-input, one-output regulator. Its inputs are speed

error e and change of error Δe . Each normalized input uses seven triangular linguistic sets: negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), and positive big (PB). Error is normalized by 12 rad/s and change of error by 50 rad/s². The output is represented by seven singleton levels from -1 to $+1$, scaled by 24 V and added around a 12 V nominal feed-forward command. The rule surface is intentionally derivative-aware: when the motor is approaching the set point rapidly, the output is reduced even if the instantaneous error is still positive. This mechanism suppresses overshoot without requiring explicit gain scheduling.

Table 2. Fuzzy rule base (rows: error e ; columns: change of error Δe)

$e / \Delta e$	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NM	NS	ZE
NM	NB	NB	NM	NM	NS	ZE	PS
NS	NB	NM	NM	NS	ZE	PS	PM
ZE	NM	NM	NS	ZE	PS	PM	PM
PS	NM	NS	ZE	PS	PM	PM	PB
PM	NS	ZE	PS	PM	PM	PB	PB
PB	ZE	PS	PM	PM	PB	PB	PB

4. Comparative Simulation Procedure and Performance Metrics

Both controllers are simulated using the same numerical integration step of 1 ms for 6 s. At $t = 0$, the speed reference is stepped from 0 to 60 rad/s. No load torque is applied during the first 3 s. At $t = 3$ s, a constant 0.15 N·m load torque is introduced and maintained to the end of the test. The same ± 24 V control limit is imposed on both algorithms. No random noise is added so that the intrinsic transient behavior of the two control laws can be compared directly.

Performance is quantified by: (i) 10–90% rise time; (ii) 2% settling time before the disturbance; (iii) percentage overshoot; (iv) steady-state error immediately before the load step; (v) maximum absolute speed deviation after the disturbance; (vi) time required to re-enter the $\pm 2\%$ speed band; (vii) integral absolute error, $IAE = \int |e(t)| dt$; and (viii) root-mean-square error, $RMSE = \sqrt{[(1/T) \int e^2(t) dt]}$. These indicators jointly measure rapidity, damping, accuracy, and disturbance robustness.

5. Reproducibility, Controller Fairness, and Implementation Sequence

To preserve fairness, the comparison changes only the control law. Motor parameters, initial conditions, speed command, numerical solver, sampling interval, voltage saturation, and load torque are identical for both tests. The controller outputs are applied directly as armature-voltage commands; therefore, neither controller receives an additional filter or actuator advantage. The PID includes only conditional anti-windup because saturation without anti-windup would unfairly penalize the integral term. The fuzzy controller uses a fixed rule base throughout the test and does not adapt online, so the comparison is between a conventional fixed-gain PID and a conventional fixed-rule FLC rather than between PID and a more complex learning controller.

The reproducible simulation sequence is: initialize speed and current to zero; apply the 60 rad/s reference at $t = 0$; calculate error and error change; calculate either the PID voltage or fuzzy voltage; saturate the voltage to ± 24 V; update armature current from the electrical equation; update rotor speed from the mechanical equation; store speed, voltage, and error; apply the 0.15 N·m load at 3 s; continue the same loop until 6 s; and finally compute the performance indicators from the recorded arrays. In MATLAB/Simulink, the same procedure can be implemented using a DC-motor state-space subsystem, a PID Controller block for the conventional case, and a Fuzzy Logic Controller block for the FLC case. The load torque can be generated with a Step block and the voltage limit with a Saturation block.

Sensitivity should also be considered when reproducing the study. PID performance is expected to change when K_p , K_i , or K_d is modified, while fuzzy performance depends on input scaling, output scaling, membership overlap, and the rule matrix. For this reason, the reported numerical results correspond specifically to the parameters listed in this methodology. The purpose is not to identify a universal optimum, but to establish a transparent benchmark under which both methods can be replicated and then returned by another researcher.

Results

Figure 2 shows the simulated responses under the common test sequence. Both controllers reach the 60 rad/s command and remain stable. The PID controller accelerates slightly faster, reaching the 10–90% rise interval in 0.509 s, whereas the fuzzy controller requires 0.591 s. The additional fuzzy damping is beneficial after the speed approaches the set point: its overshoot is 2.84%, compared with 4.74% for PID, and its 2% settling time is reduced from 2.602 s to 1.202 s.

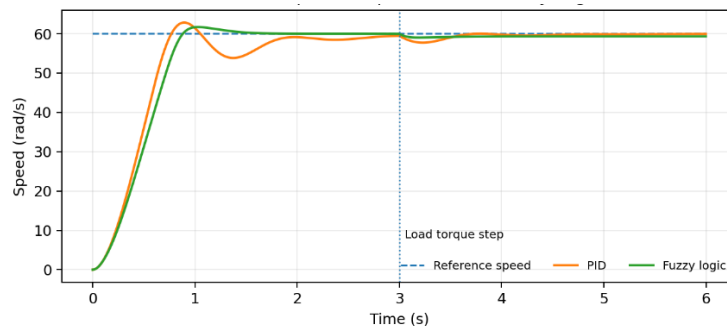


Figure 2. Simulated speed responses for PID and fuzzy logic controllers. The vertical marker at 3 s denotes the 0.15 N·m load-torque step.

Table 3. Comparative performance obtained from the simulation

Performance metric	PID	Fuzzy logic
Rise time (s)	0.509	0.591
Settling time, $\pm 2\%$ (s)	2.602	1.202
Overshoot (%)	4.74	2.84
Steady-state error before load (rad/s)	0.531	≈ 0.000
Maximum load-induced deviation (rad/s)	2.274	0.973
Recovery to $\pm 2\%$ band after load (s)	0.462	0.000*
Integral absolute error, IAE	32.164	31.623
RMSE (rad/s)	14.107	14.621

The disturbance test gives the clearest difference. The load step produces a maximum PID speed deviation of 2.274 rad/s (approximately 3.79% of the reference), and the response needs about 0.462 s to return to the $\pm 2\%$ band. Under fuzzy control, the maximum deviation is 0.973 rad/s (approximately 1.62%), which never leaves that band. The pre-disturbance fuzzy steady-state error is essentially zero in the numerical model, while PID retains about 0.531 rad/s at the sampling instant immediately before the load is applied.

The IAE values are close, with a small advantage for fuzzy control (31.623 versus 32.164). RMSE is slightly lower for PID because the faster initial acceleration reduces the large early step error, even though PID has greater overshoot and disturbance deviation. This illustrates why a single error index should not be used to declare one controller universally superior. For applications in which rapid initial acceleration is dominant, the PID response is attractive. For applications where smooth settling, low overshoot, and load-disturbance containment are more important, the FLC provides the better overall transient profile.

From a practical design perspective, the response curves indicate two different tuning philosophies. The PID controller drives the actuator strongly during the initial large error and therefore reaches the target region earlier. The fuzzy controller also saturates during the large-error phase, but its rule surface reduces command more progressively as the error derivative becomes negative. This produces a less aggressive approach to the reference and explains the smaller overshoot and shorter final settling time. After the load is applied, the fuzzy rule base immediately increases voltage according to both the renewed positive error and its rate of change, which limits the speed dip. These mechanisms are consistent with the qualitative advantages reported in earlier fuzzy-motor-control studies [3]–[10].

Conclusion and Discussion

This comparative methodology demonstrates how PID and fuzzy logic controllers can be evaluated fairly for DC motor speed control by using a common motor model, voltage saturation, reference command, disturbance profile, and performance criteria. The simulated PID controller offers the shortest rise time and slightly lower global RMSE, confirming the continued value of fixed-gain PID control for simple, computationally inexpensive drive regulation. However, the fuzzy logic controller substantially improves several quality-of-response indicators: overshoot falls from 4.74% to 2.84%, settling time decreases from 2.602 s to 1.202 s, pre-load steady-state error becomes negligible, and the load-induced speed deviation remains inside the $\pm 2\%$ band. These findings are consistent with the pre-2017 literature, which repeatedly reports that fuzzy or adaptive fuzzy methods can improve robustness and transient quality in DC and BLDC drives [3]–[10]. The reason is structural: fuzzy rules can vary the effective control action according to the magnitude and trend of the error, whereas a conventional PID uses the same gains across all operating conditions. Nevertheless, fuzzy control introduces additional design choices—membership functions, scaling factors, rule selection, and defuzzification—and therefore requires systematic validation rather than informal rule tuning. The present results should be interpreted as simulation evidence, not laboratory measurements. Future experimental work should include encoder quantization, PWM switching, sensor noise, current limits, Coulomb friction, parameter uncertainty, and changing inertia. A useful extension would compare optimized PID, type-1 fuzzy, fuzzy-PID, and interval type-2 fuzzy controllers on the same physical motor. Within the scope of this paper, the FLC is recommended when low overshoot and disturbance robustness are primary objectives; PID is recommended when implementation simplicity and very fast initial response are more important.

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