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

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Abstract

This paper presents a comparative methodology for proportional-integral-derivative (PID) and fuzzy logic control of a permanent-magnet DC motor. The study uses the same motor model, actuator voltage limit, reference command, and load-disturbance profile so that the two control strategies are evaluated under identical conditions. A conventional PID controller is implemented using speed error, integral action, and derivative action, while a Mamdani-type fuzzy controller uses speed error and change of error with five linguistic sets and a rule base, together with a small integral bias to remove steady-state offset. The motor is commanded from rest to 500 rpm and a 0.25 N·m load disturbance is applied at 4 s. Performance is assessed using rise time, settling time, percentage overshoot, steady-state error, disturbance-induced speed drop, and recovery time. In the simulation reported here, the fuzzy controller provides a faster rise time (0.298 s versus 0.547 s), whereas the PID controller gives much lower overshoot (0.10% versus 16.36%) and a shorter nominal settling time. Disturbance rejection is similar for the two controllers. The comparison therefore shows that controller selection should be based on the required balance among rapid acceleration, damping, robustness, and implementation complexity rather than on a single performance index.

Introduction

DC motors remain important in variable-speed drives, laboratory servos, robotics, conveyors, and embedded motion systems because the relationship among armature voltage, torque, current, and speed can be represented by a compact electromechanical model. Nevertheless, practical speed regulation is affected by load torque, supply limits, friction, parameter variation, and measurement noise. These effects make the controller responsible not only for tracking the desired speed but also for maintaining acceptable transient behavior when operating conditions change. The PID controller is a standard solution because it is simple, computationally light, and supported by established tuning procedures. The classical

work of Ziegler and Nichols [1] helped formalize systematic PID tuning and remains influential in conventional feedback design.

Fuzzy control provides a different design philosophy. Zadeh's fuzzy-set framework [2] represents imprecise concepts through graded membership rather than binary membership, and Mamdani and Assilian [3] demonstrated how linguistic rules can be converted into a practical feedback controller. For motor control, this means that an engineer can encode rules such as 'if speed error is positive large and the error is still increasing, apply a large positive correction' without requiring the controller law to be derived solely from an exact plant model. Early fuzzy-PID work on DC servo systems [4] and fuzzy speed control of shunt DC motors [5]

showed the feasibility of rule-based control for electric-drive applications.

The objective of this paper is to construct a controlled and reproducible comparison of a conventional PID controller and a fuzzy logic controller for DC motor speed control using literature available up to and including 2015. The study focuses on methodology: the same motor, reference command, disturbance, voltage constraint, and performance definitions are used for both controllers. This avoids a common weakness in comparative studies in which controllers are tested with different plant assumptions or tuned against different objectives. The resulting comparison is intended to show both the strengths and the trade-offs of the two approaches.

Literature Review

The literature prior to 2016 shows a progression from direct fuzzy speed control toward adaptive and hybrid fuzzy-PID structures. Nam and Yoo [4] proposed fuzzy PID reasoning for DC servo motors and reported the potential of fuzzy inference to improve controller behavior while retaining PID-like action. Saneifard et al. [5] used a shunt DC motor as a practical fuzzy-control application and demonstrated how motor speed could be regulated through a fuzzy rule base. These studies established the relevance of fuzzy reasoning to electromechanical speed control and highlighted its ability to incorporate qualitative operating knowledge.

Research in 2012-2015 increasingly examined embedded implementation and online

adaptation. Arulmozhiyal and Kandiban [6] designed a fuzzy PID controller for a brushless DC motor, and Kandiban and Arulmozhiyal [7] compared conventional and adaptive fuzzy PID speed control, emphasizing the difficulty of fixed-gain PID tuning when operating conditions vary. Sarin et al. [8] demonstrated fuzzy PID control on an 8-bit microcontroller, which is relevant to low-cost embedded implementation. Sadiq et al. [9] applied fuzzy speed control to a separately excited DC motor using coordinated armature-voltage and field-current control, illustrating the flexibility of fuzzy rules across more than one control input.

Hardware-oriented studies further strengthened the case for intelligent motor control. Ramadan et al. [10] implemented a real-time fuzzy motor speed controller and later reported an improved adaptive fuzzy controller implemented on an FPGA [11]. Premkumar and Manikandan [12] extended the comparison to an adaptive neuro-fuzzy inference system for brushless DC motor speed control. Yau et al. [13] combined optimized PID gains with fuzzy fine tuning for a DC servo motor, while Fereidouni et al. [14] developed an adaptive PID-type fuzzy configuration and analyzed its behavior across operating conditions. Collectively, these studies indicate that PID remains attractive for simplicity and predictable tuning, while fuzzy and fuzzy-assisted controllers are useful when nonlinear behavior, uncertainty, adaptation, or linguistic design knowledge is important.

Table 1. Selected literature relevant to the comparison (all references are 2015 or earlier).

Ref.	Year	Controller / platform	Contribution to this study
[5]	1998	Fuzzy DC motor	Demonstrated rule-based fuzzy speed regulation on a shunt DC motor.
[6]	2012	Fuzzy-PID BLDC	Applied fuzzy tuning to motor speed control and motivated comparison with fixed gains.
[8]	2012	8-bit fuzzy PID	Showed that fuzzy PID can be implemented on resource-limited embedded hardware.
[10]	2014	Real-time fuzzy	Reported real-time fuzzy speed control with practical embedded implementation.
[12]	2014	ANFIS / fuzzy-PID	Compared intelligent speed-control approaches for a BLDC motor.
[14]	2015	Adaptive fuzzy PID	Demonstrated adaptive PID-type fuzzy configuration and robustness-oriented tuning.

Methodology

The methodology is organized as a seven-step simulation procedure. The central principle is controlled comparison: only the controller is changed, while the DC motor, limits, command signal, disturbance, simulation step size, and performance calculations remain identical. The architecture is shown in Figure 1. This structure

is consistent with prior motor-control comparisons in which conventional and fuzzy approaches are evaluated on a common drive model [6], [7], [10].

Step 1: Develop the DC motor model

A permanent-magnet DC motor is represented by the standard armature and mechanical

equations. The electrical equation is $V_a(t) = L_a(di_a/dt) + R_a i_a + K_b \omega$, and the mechanical equation is $J(d\omega/dt) + B\omega = K_t i_a - T_L$. Eliminating armature current gives the speed

transfer function $G(s) = K_t / [(L_a s + R_a)(Js + B) + K_t K_b]$. The parameters in Table 2 define a compact low-voltage motor suitable for a comparative control simulation.

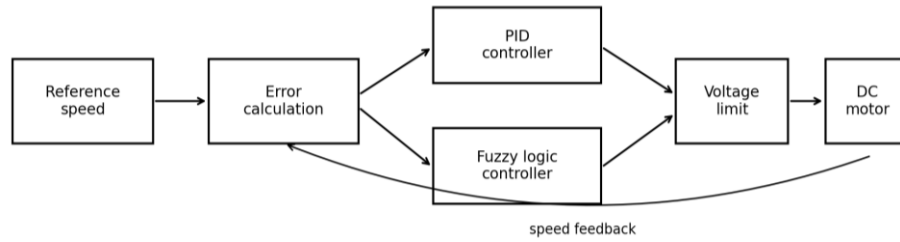


Figure 1. Common comparison framework for PID and fuzzy logic speed control.

Table 2. DC motor and simulation parameters.

Parameter	Symbol	Value	Unit
Armature resistance	R_a	1.0	Ω
Armature inductance	L_a	0.05	H
Torque constant	K_t	0.10	N·m/A
Back-emf constant	K_b	0.10	V·s/rad
Rotor inertia	J	0.010	kg·m ²
Viscous friction	B	0.020	N·m·s/rad
Voltage limit	V_{max}	± 24	V
Speed command	ω_r	500	rpm
Load step at 4 s	T_L	0.25	N·m

Step 2: Configure the PID controller

The PID control law is $u_{PID}(t) = K_p e(t) + K_i \int e(t) dt + K_d de(t)/dt$, where $e(t) = \omega_r(t) - \omega(t)$. A moderate fixed-gain tuning is used so the controller is stable, well damped, and representative of a conventional design. The selected gains are $K_p = 0.30$, $K_i = 1.00$, and $K_d = 0.001$. The control voltage is limited to ± 24 V, and conditional integration is used as a basic anti-windup measure. The use of proportional, integral, and derivative terms follows the conventional PID framework associated with classical tuning practice [1].

Step 3: Configure the fuzzy logic controller

The fuzzy controller uses two normalized inputs: speed error e and change of error Δe . Each input is represented by five triangular/shoulder membership sets: negative-big (NB), negative-small (NS), zero (Z), positive-small (PS), and positive-big (PB). A 5×5 Mamdani-type rule base maps the two inputs to a normalized corrective command. The rules increase positive control action when positive error is large, reduce the command as the error approaches zero, and reverse the correction when speed exceeds the reference. Centroid/weighted singleton defuzzification produces a crisp output. The linguistic structure follows the fuzzy-control principles introduced by Zadeh [2] and Mamdani and Assilian [3], and is consistent with fuzzy motor-speed implementations reported in [5], [9], and [10].

To ensure that a nonzero motor voltage is available at zero tracking error, the fuzzy correction is added to the motor's approximate steady-state voltage for the reference speed, $u_0 = (R_a B / K_t + K_b) \omega_r$, and a small integral bias removes residual offset. The scaling values used in the study are $K_e = 2.0$ for normalized error, $K_{\Delta e} = 0.004$ for change of error, fuzzy output scale $K_f = 6.0$ V, and integral-bias gain $K_{if} = 1.0$. This is a fuzzy logic speed controller rather than a conventional PID: the dominant nonlinear corrective action is generated by the rule base.

Step 4: Apply an identical test profile

Both controllers start from rest. At $t = 0.2$ s, the speed reference is stepped to 500 rpm. The motor initially operates without external load so that command tracking can be measured. At $t = 4.0$ s, a 0.25 N·m shaft-load disturbance is applied and held until the end of the 7 s simulation. The numerical integration step is 1 ms. No motor parameter, voltage limit, reference value, or disturbance is changed between the PID and fuzzy runs.

Step 5: Measure controller performance

Six metrics are calculated. Rise time is the interval required for the speed to move from 10% to 90% of the 500 rpm command. Percentage overshoot is measured relative to the reference. Settling time is the time after the command step at which speed enters and remains within a $\pm 2\%$ band. Steady-state error is evaluated immediately before the load step. Disturbance

speed drop is the maximum percentage reduction after the 0.25 N·m load is applied, and recovery time is the time required to re-enter the same $\pm 2\%$ band. These metrics separate nominal command-following performance from load-rejection behavior.

The two speed trajectories are plotted on the same axes to expose differences in acceleration, overshoot, damping, and post-disturbance recovery

Step 6: Generate response curves and comparison table

The computed metrics are then placed in a common table. Because all test conditions are identical, differences in the results can be attributed to the control law and its selected tuning rather than to a change of motor model or disturbance level.

Step 7: Interpret the trade-offs

The final step evaluates which controller characteristic is preferable for a given application. A drive that cannot tolerate overshoot may favor the more strongly damped

PID tuning, whereas an application that prioritizes rapid acceleration or must encode nonlinear operating knowledge may favor fuzzy control. Previous embedded and adaptive fuzzy studies [8], [11], [13], [14] also indicate that implementation platform, computational cost, and adaptation requirements should be considered alongside time-domain performance.

Results

Figure 2 shows the simulated speed responses. Both controllers track the 500-rpm command and both reject the applied load without instability. The principal difference occurs during the initial acceleration. The fuzzy controller reaches 90% of the command sooner, but its more aggressive nonlinear correction produces a pronounced overshoot. The PID controller rises more slowly but is strongly damped and settles near the reference with very little overshoot. After the load disturbance at 4 s, the speed dips by approximately 6.3-6.4% for both controllers and then recovers.

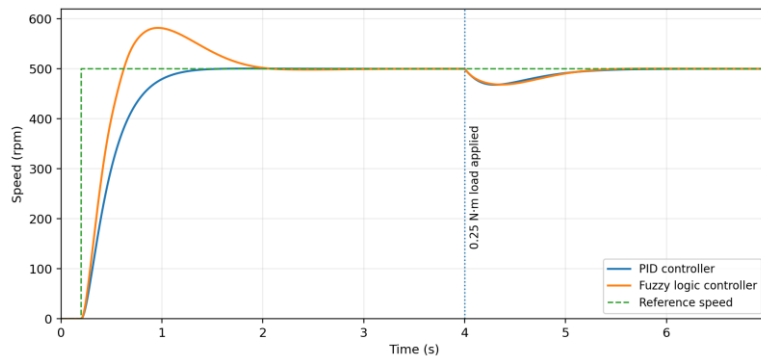


Figure 2. Simulated PID and fuzzy speed responses for a 500-rpm command and a 0.25 N·m load disturbance at 4 s.

Table 3. Performance comparison from the common simulation test.

Performance metric	PID	Fuzzy logic	Interpretation
Rise time (10-90%)	0.547 s	0.298 s	Fuzzy is faster
Overshoot	0.10%	16.36%	PID is much better damped
Settling time ($\pm 2\%$)	0.936 s	1.596 s	PID settles sooner
Pre-load steady error	0.0002 rad/s	0.0010 rad/s	Both are near zero
Load-induced speed drop	6.39%	6.32%	Nearly identical
Recovery after load	0.942 s	0.983 s	Similar recovery time

The rise-time reduction produced by the fuzzy controller is approximately 45.5% relative to the selected PID tuning. This advantage is accompanied by a large increase in overshoot, from about 0.10% to 16.36%, and by a longer settling time. The result is physically consistent with an aggressively scaled rule base: large positive error activates strong control effort, which accelerates the motor rapidly, while the transition from positive to braking correction occurs later than in the well-damped PID

response. The comparison therefore illustrates why fuzzy-controller scaling and membership design are as important as PID gain tuning. Disturbance rejection is much closer. The maximum speed drop is 6.39% for PID and 6.32% for fuzzy control, while the recovery times are 0.942 s and 0.983 s, respectively. Thus, under the specific fixed load step used here, neither controller has a decisive disturbance-rejection advantage. More complex adaptive fuzzy controllers reported in the literature [11], [14]

address this limitation by changing the control law or scaling online rather than retaining one fixed rule configuration.

Conclusion and Discussion

This methodology paper compared PID and fuzzy logic speed control of the same DC motor under identical reference, voltage, and load conditions. The conventional PID controller provided the best damping in the selected experiment: it produced negligible overshoot and a short settling time. The fuzzy controller produced a substantially faster rise time but at the cost of larger overshoot and slower settling. Both controllers achieved very small steady-state error and broadly similar rejection of the imposed 0.25 N·m load disturbance. The results show that a fuzzy controller should not automatically be assumed to outperform PID in every time-domain metric; performance depends strongly on membership functions, rule design, scaling factors, and any adaptive mechanism used. From an implementation perspective, PID remains attractive when the motor model is reasonably stable, computational resources are limited, and a transparent gain-tuning process is desired. Fuzzy logic becomes more compelling when the operating behavior is nonlinear, uncertain, or difficult to express as a single fixed-gain control law. Pre-2016 work on real-time fuzzy motor control [10], FPGA-based adaptive control [11], optimized fuzzy-PID servo control [13], and adaptive PID-type fuzzy configurations [14] supports this broader interpretation. A useful extension of the present study would therefore keep the same common test protocol but add parameter variation, sensor noise, repeated load steps, and an adaptive fuzzy scaling mechanism. That extension would test whether the flexibility reported in the literature translates into measurable robustness gains beyond the nominal operating point.

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