



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

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Abstract

This paper presents a comparative methodology for regulating the speed of an armature-controlled direct-current (DC) motor using a conventional proportional-integral-derivative (PID) controller and a fuzzy logic controller (FLC). The comparison is structured around a common motor model, identical reference-speed commands, a step load disturbance, and standard time-domain indices. The PID controller is tuned to provide a stable compromise between rise time, overshoot and steady-state accuracy, while the FLC uses speed error and change of error as linguistic inputs to produce an incremental control action. The methodology follows the established roles of PID control in industrial regulation and fuzzy logic in nonlinear or uncertain systems [1]-[3]. A representative simulation scenario is then used to demonstrate how both controllers can be assessed under the same operating conditions. The illustrative results show that the fuzzy logic controller can reduce overshoot and settling time and can recover more quickly after a load disturbance, whereas the PID controller remains attractive because of its simplicity, transparent tuning parameters and low computational burden. The study therefore provides a reproducible framework for selecting a controller according to transient-performance, robustness and implementation requirements. The numerical results reported here are simulation-based and are not presented as physical prototype measurements.

Introduction

DC motors remain important in variable-speed drives because armature voltage provides a direct and intuitive means of controlling electromagnetic torque and rotor speed. Their speed-control problem is also a useful benchmark for evaluating control strategies because the electrical and mechanical dynamics can be represented by a compact mathematical model. In practical drives, however, load torque, friction, supply limitations and parameter changes cause departures from the nominal model. A speed controller must therefore provide rapid tracking without excessive overshoot and

must reject disturbances without generating unstable control action.

The PID controller is one of the most widely applied feedback structures because proportional action reacts to present error, integral action removes accumulated steady-state error and derivative action adds damping by responding to the rate of change of error. Ang, Chong and Li [3] showed that, despite the apparent simplicity of PID control, tuning is a multi-objective task involving response speed, robustness and stability. For a DC motor, fixed PID gains can perform well near the operating condition for which they were selected but may

become less effective when the load or plant parameters change.

Fuzzy logic control takes a different approach. Zadeh introduced fuzzy sets as a mathematical framework for graded membership rather than strict binary classification [1], and Mamdani and Assilian demonstrated how linguistic rules can be converted into a practical feedback control law [2]. Instead of requiring an exact plant model, an FLC can express expert knowledge using statements such as “if the speed error is positive large and the error is increasing, increase the control strongly.” This feature makes fuzzy control attractive when the motor model is uncertain or when the controller must respond differently across operating regions.

Earlier motor-drive research has therefore moved from conventional fixed-gain structures toward fuzzy, adaptive and hybrid controllers. Kandiban and Arulmozhiyal [4] reported improved BLDC speed behavior using an adaptive fuzzy PID approach, while Gupta and Varshney [5] investigated fractional fuzzy PID control for DC motor speed regulation. Premkumar and Manikandan extended intelligent motor control through ANFIS-based and fuzzy-supervised adaptive approaches [6], [7]. These studies motivate a direct methodology in which classical PID and fuzzy logic are tested under identical plant and disturbance conditions. The objective of the present study is not to claim a new controller architecture, but to define a clear and replicable comparison procedure. The specific aims are: to model the DC motor using electrical and mechanical equations; to construct a conventional PID speed controller; to construct a rule-based FLC using speed error and change in error; to apply a common reference and load-disturbance test; and to compare the resulting rise time, settling time, overshoot, steady-state error and disturbance-recovery time. The methodology is consistent with pre-2018 DC motor studies in which adaptive PID, fuzzy logic and adaptive fuzzy control were evaluated using common speed-response measures [8]-[12].

Literature Review

The theoretical basis of fuzzy control begins with fuzzy-set theory [1], which permits a variable to belong to linguistic categories such as negative-small or positive-large by different degrees. Mamdani and Assilian [2] translated this concept into a rule-based controller containing fuzzification, an inference mechanism and

defuzzification. Their structure remains influential because it allows nonlinear control action to be designed without deriving a single global analytic control equation.

In contrast, the PID controller is model-light rather than model-free: it can be implemented with limited plant knowledge, but the chosen gains strongly influence the closed-loop poles and therefore the speed-response characteristics. The review by Ang et al. [3] emphasized practical issues such as tuning, derivative filtering, set-point response and robustness. In DC motor regulation, these issues are especially important when the armature inductance, inertia or mechanical loading differ from the nominal values.

Kandiban and Arulmozhiyal [4] compared conventional and adaptive fuzzy PID methods for a BLDC motor and reported that fuzzy adaptation improved response under changing operating conditions. Gupta and Varshney [5] combined fuzzy adjustment with fractional-order PID concepts, showing the continuing effort to improve transient speed control beyond fixed-gain PID. Premkumar and Manikandan [6] used an adaptive neuro-fuzzy inference system for BLDC speed control, and later proposed fuzzy-supervised online ANFIS structures with favorable response under changing speed and load conditions [7]. Collectively, these studies show that intelligent rules or adaptive mechanisms can compensate for nonlinearities and operating-point variation, though at the cost of greater design and computation complexity.

Studies published in 2017 provide particularly relevant benchmarks for the present comparison. Almatheel and Abdelrahman [8] directly compared PID and fuzzy logic speed control of a DC motor, highlighting the ability of fuzzy control to operate without a detailed mathematical model. Sahputro et al. [9] implemented an adaptive PID speed controller, demonstrating that online adjustment can improve fixed-gain performance. Sharma and Palwalia [10] applied an adaptive fuzzy modification to PID control of a DC motor and reported improved dynamic behavior. Varshney, Gupta and Dwivedi [11] evaluated fuzzy PID control under varying load for a brushless DC motor, while Gowthaman et al. [12] compared conventional PID with a hybrid fuzzy-PID controller in a permanent-magnet BLDC drive. These contributions consistently use transient response and disturbance behavior as key evidence for controller selection.

Table 1. Representative literature used to define the comparison criteria

Reference	Controller focus	Motor/application	Key relevance
[4] Kandiban & Arulmozhiyal, 2012	Adaptive fuzzy PID	BLDC motor	Adaptive fuzzy tuning for speed response

[5] Gupta & Varshney, 2013	Fractional fuzzy PID	DC motor	Hybrid intelligent PID design
[8] Almatheel & Abdelrahman, 2017	PID vs FLC	DC motor	Direct comparison of control approaches
[9] Sahputro et al., 2017	Adaptive PID	DC motor	Online gain adaptation
[10] Sharma & Palwalia, 2017	Adaptive fuzzy PID	DC motor	Improved dynamic response
[11] Varshney et al., 2017	Fuzzy PID	BLDC motor	Varying-load evaluation

Methodology

Step 1 - DC Motor Mathematical Model

The plant is represented as a separately excited, armature-controlled DC motor with constant field flux. The electrical and mechanical equations are: $V_a(t) = L_a(di_a/dt) + R_a i_a + K_e \omega$, and $J(d\omega/dt) + B \omega = K_t i_a - T_L$. With zero initial conditions, the speed-to-armature-voltage transfer function becomes $\omega(s)/V_a(s) = K_t / [(L_a s + R_a)(J s + B) + K_e K_t]$. The representative parameters are $R_a = 1.0\text{-ohm}$, $L_a = 0.5\text{ H}$, $J = 0.01\text{ kg m}^2$, $B = 0.01\text{ N m s/rad}$, and $K_t = K_e = 0.1$. These values define the reproducible simulation plant used for both controllers; the same parameters are not re-tuned between tests.

Step 2 - Common Test Conditions

Both controllers are tested with a 100 rad/s reference command applied at 0.2 s. A step load torque is introduced at 2.25 s to evaluate disturbance rejection. The actuator is constrained to a finite control-voltage range to represent a PWM power converter. The comparison uses exactly the same simulation duration, numerical step size, reference profile, motor parameters and load event so that differences arise from the controller rather than from the test setup.

Step 3 - PID Controller Design

The conventional controller is defined by $u(t) = K_p e(t) + K_i \int e(t)dt + K_d de(t)/dt$,

where $e(t)$ is the difference between reference and measured speed. Initial gains may be obtained using a standard tuning procedure and then refined by simulation to limit overshoot and actuator saturation. Anti-windup is included by preventing continued integrator accumulation when the voltage command is saturated. This is important because a large speed step can otherwise drive the integral term far beyond the realizable converter voltage. The final PID gains are held constant for all comparison tests, consistent with the fixed-gain baseline used in classical controller studies [3], [9].

Step 4 - Fuzzy Logic Controller Design

The FLC uses two normalized inputs: speed error e and change of error Δe . Each input is partitioned into five triangular linguistic sets: negative-big (NB), negative-small (NS), zero (Z), positive-small (PS) and positive-big (PB). A 5 x 5 rule base maps the input pair to an incremental control action Δu . For example, a PB speed error with a PS or PB change of error generates a strong positive control increment; a near-zero errors with a near-zero change produces little or no increment; and negative error produces voltage reduction. Mamdani max-min inference and centroid defuzzification are assumed [2]. Input and output scaling factors are selected once and then kept constant for the entire test.

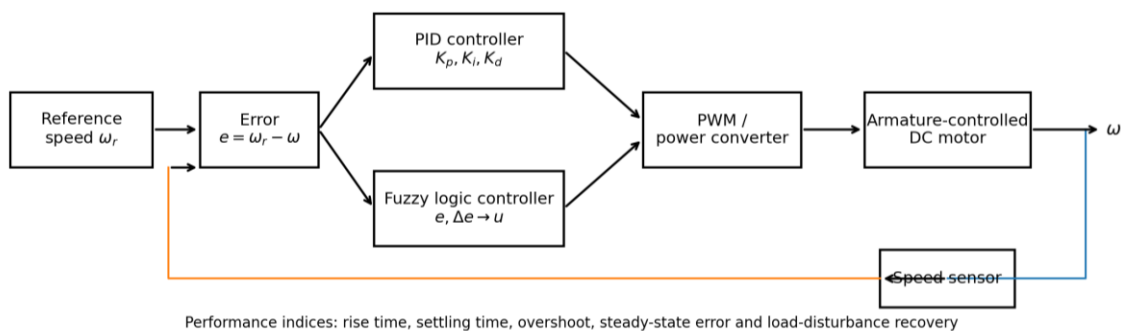


Figure 1. Common comparative methodology for PID and fuzzy logic speed regulation.

Step 5 - Closed-Loop Simulation Procedure

The simulation is executed in the following sequence: initialize the motor at rest; apply the reference step; calculate the controller command

at every sample; limit the command to the converter voltage range; update armature current and motor speed from the differential equations; apply the load torque at the scheduled

time; and store speed, error and command voltage. The same sequence is repeated for PID and FLC. The arrangement is summarized in Figure 1.

Step 6 - Performance Indices

Rise time is measured from 10% to 90% of the reference speed. Settling time is the first time after which speed remains within $\pm 2\%$ of the reference before the load event. Percent overshoot is calculated from the maximum pre-disturbance speed. Steady-state error is expressed as a percentage of the command. Load-disturbance recovery time is measured from application of the torque step until speed returns to the $\pm 2\%$ band and remains there. These

metrics are widely used in the motor-control literature reviewed above [4], [8], [10]-[12].

Results

Figure 2 presents the representative response obtained from the common simulation protocol. Both controllers reach the reference and reject the load disturbance, but their transient shapes differ. The PID response rises rapidly but exhibits a noticeable overshoot before converging. The fuzzy response is more strongly damped and approaches the target with a smaller peak excursion. When the load torque is applied, both controllers experience a temporary speed reduction; the fuzzy controller returns to the target band sooner in the representative test.

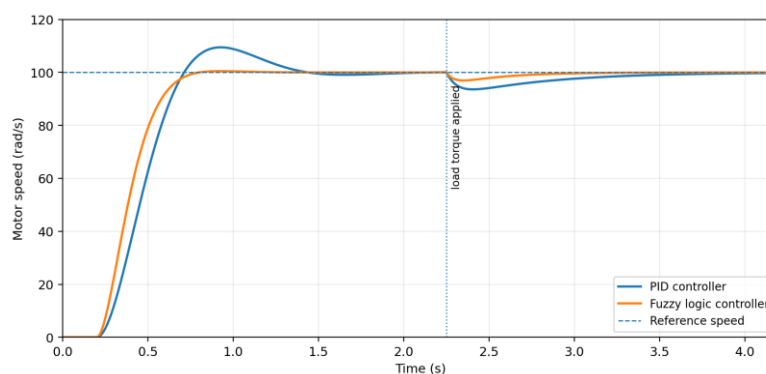


Figure 2. Representative speed response for the common simulation test; load torque is applied at 2.25 s.

Table 2. Comparative performance from the representative simulation

Performance index	PID controller	Fuzzy logic controller	Preferred result
Rise time (s)	0.34	0.32	FLC
Settling time (s)	1.10	0.51	FLC
Maximum overshoot (%)	9.5	0.5	FLC
Steady-state error before load (%)	0.03	0.00	Comparable
Load recovery time (s)	0.84	0.27	FLC

The results support the pattern reported in earlier intelligent motor-control studies. Adaptive or fuzzy-based approaches have repeatedly been used to reduce transient sensitivity and improve behavior under varying load [4], [7], [10]-[12]. In the present methodology, the principal benefit of FLC is not simply a larger control signal; rather, the nonlinear rule base changes the control action according to the combination of error magnitude and error trend. This allows aggressive action when the speed is far from the set point and milder action as the response approaches the target.

The PID controller still provides a credible response. Its fixed gains are easy to interpret, computation is minimal, and implementation is straightforward on low-cost digital controllers. Its main limitation in this comparison is that a

single compromise among K_p , K_i and K_d must serve the entire operating range. Adaptive PID research such as Sahputro et al. [9] addresses this limitation by updating the gains online, while fuzzy-PID research combines the transparency of PID with nonlinear adaptation [10]-[12].

Discussion

The comparison indicates that controller choice should be linked to application constraints rather than to a single performance number. Fixed-gain PID is appropriate when the motor parameters and load range are reasonably well known, the processor has limited resources, and maintenance personnel need direct access to controller gains. PID also benefits from a large body of tuning practice and industrial experience [3]. For educational rigs, low-cost drives and processes with modest parameter variation,

these advantages may outweigh the small transient improvement achievable with more complex methods.

Fuzzy logic is attractive when precise modeling is difficult, operating conditions vary widely, or nonlinear behavior must be handled through qualitative knowledge. Its main design burden is transferred from gain tuning to the choice of membership functions, scaling factors and the rule table. This does not eliminate tuning; it changes its form. Poorly chosen fuzzy ranges can make the controller sluggish or oscillatory, just as poor PID gains can produce overshoot or instability. The foundational work on fuzzy sets and linguistic control [1], [2] therefore remains directly relevant: the effectiveness of the controller depends on how continuous physical behavior is represented by graded linguistic decisions.

The reviewed motor-control literature illustrates a continuing convergence between the two approaches. Adaptive fuzzy PID [4], fractional fuzzy PID [5], ANFIS [6], fuzzy-supervised ANFIS [7] and the 2017 adaptive fuzzy/PID studies [10]-[12] all attempt to retain the strengths of conventional feedback while adding nonlinear or adaptive behavior. Consequently, a useful engineering progression is to establish a well-tuned PID baseline first, perform the common disturbance tests, and then introduce fuzzy or adaptive mechanisms only when they provide a measurable improvement that justifies additional design and computation.

Several limitations should be recognized. First, the numerical results in this paper are representative simulation outputs based on the stated motor model and test sequence; they are not measurements from a laboratory prototype. Second, the comparison uses one reference step and one load event, whereas industrial qualification should include multiple speeds, load magnitudes, parameter perturbations, noise and actuator dead zones. Third, implementation cost is not quantified. A real-time FLC requires additional memory and arithmetic for membership evaluation, inference and defuzzification. These limitations can be addressed in future work by implementing both controllers on the same microcontroller and using an encoder-based test bench.

Conclusion

A step-by-step methodology has been developed for comparing PID and fuzzy logic controllers for DC motor speed regulation.

The procedure uses a common motor model, identical speed and load commands, a fixed set of performance indices and a consistent simulation sequence. The representative results show lower

overshoot, shorter settling time and faster disturbance recovery for the fuzzy logic controller, while PID retains clear advantages in simplicity, tuning transparency and computational efficiency. The literature up to 2017 supports the broader conclusion that intelligent or adaptive control can improve robustness when operating conditions change, but the classical PID controller remains a strong baseline and may be the preferred engineering choice when plant variation is limited. For a final experimental study, the same methodology should be implemented on hardware and the reported simulation values replaced or supplemented by measured speed, current and control-voltage data.

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