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International Journal of Advanced Electrical and Electronics Engineering

ISSN: 2278-8948

Volume 05 Issue 01, 2016

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

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Peer Review Information

Submission: 08 Jan 2016

Revision: 04 Feb 2016

Acceptance: 09 March 2016

Keywords

DC Motor, PID Controller, Fuzzy Logic Controller, Speed Regulation, MATLAB/Simulink

Abstract

This paper presents a reproducible methodology for comparing a conventional proportional-integral-derivative (PID) controller with a fuzzy logic controller (FLC) for closed-loop speed regulation of a separately excited DC motor. A common electromechanical motor model, identical reference-speed command, actuator saturation and load-disturbance profile are used so that differences arise from the controller rather than the plant. The PID design uses fixed gains with derivative filtering and anti-windup, whereas the FLC uses speed error and change of error as linguistic inputs, five triangular membership functions per input, a 25-rule base and centroid-equivalent weighted defuzzification. The controllers are evaluated through rise time, settling time, percentage overshoot, steady-state error and disturbance recovery. In the illustrative simulation developed for this methodology, PID regulation gives a faster rise and settling response and stronger recovery from the applied load torque, while the FLC reduces overshoot and retains the practical advantage of rule-based control with limited dependence on an exact plant model. The study therefore emphasizes that controller selection should be based on the required trade-off among transient speed, overshoot, modeling effort and robustness rather than on a single performance index.

Introduction

DC motors remain important in variable-speed drives, positioning equipment, conveyors, robotic mechanisms and laboratory motion-control systems because armature voltage provides a direct means of controlling electromagnetic torque and speed. The main control problem is to track a demanded speed while minimizing the effect of inertia, friction, supply limits and load-torque changes. Classical PID control continues to be widely used because its proportional, integral and derivative actions offer an interpretable balance between response speed, offset removal and damping; however, fixed gains can become less effective when the

operating condition departs from that used for tuning [4].

Fuzzy logic offers a different design philosophy. Zadeh introduced fuzzy sets as a mathematical framework for representing gradual membership rather than binary classification [1], and Mamdani and Assilian showed how linguistic rules could be converted into an automatic control law [2]. In motor drives, the resulting FLC can encode statements such as "if the speed error is positive large and the error is increasing, apply a large positive correction." This is attractive when a complete analytical model is unavailable or when nonlinearities and parameter variations make fixed-gain control difficult. Early work on shunt DC motors demonstrated that fuzzy speed

regulation could be formulated as a practical engineering control problem [3].

A fair comparative study must nevertheless avoid comparing controllers under different plants, references or disturbance conditions. This paper therefore proposes a common simulation framework in which PID and FLC act on the same DC motor model, are limited by the same 24 V actuator and are tested with the same 100 rad/s reference and load-torque step. The objective is not to declare one controller universally superior, but to establish a transparent methodology that identifies where each controller is advantageous and which performance measures justify that conclusion.

Literature Review

The development of PID control is closely associated with its practical simplicity and the possibility of systematic tuning. Astrom and Hagglund observed that PID remains a central industrial feedback structure while also emphasizing issues such as saturation, integral windup and the need for improved tuning strategies [4]. For DC motor applications, Gowthaman and Balaji investigated self-tuned PID speed control of a permanent-magnet DC drive, illustrating continuing efforts to make PID behavior less dependent on a single fixed operating point [7]. Deraz later used optimization-based PID tuning for a DC motor and reported that the chosen performance criterion strongly influences rise time, overshoot and steady-state behavior [10].

Fuzzy speed control developed in parallel. Saneifard et al. presented a fuzzy-logic-based speed controller for a shunt DC motor and showed the suitability of motor speed regulation as an application for linguistic control rules [3]. Pavankumar et al. extended intelligent speed control through a neuro-fuzzy approach for a separately excited DC motor [5]. Ramadan et al.

implemented real-time fuzzy motor speed control in an embedded/FPGA-oriented framework, demonstrating that fuzzy inference can be realized in hardware rather than remaining only a simulation concept [8]. Zaki et al. subsequently reported an embedded indirect adaptive fuzzy controller with a T-S inverse model for DC motor speed control in the 2016 volume of Arabian Journal for Science and Engineering [13]. Adepoju, Adeyemi and Oni also modeled a separately excited DC motor with an FLC in MATLAB/Simulink and emphasized its adaptability without requiring a highly detailed plant model [11].

Several studies directly motivate comparative analysis. Ahmad, Kishor and Rai compared PID, internal-model and fuzzy control for a DC motor and treated transient and steady-state characteristics as the key basis for evaluation [9]. Batayneh and Nawafleh compared conventional PID with intelligent controllers for DC motor speed control and reported that controller architecture materially changes overshoot and steady-state behavior [12]. Fereidouni, Masoum and Moghbel proposed an adaptive PID-type fuzzy configuration, showing that hybrid strategies can combine PID precision with fuzzy adaptation [6]. Taken together, these works justify a controlled comparison in which motor parameters, actuator saturation and disturbance tests are held constant; they also motivate hybrid approaches when uncertainty or operating-range changes become significant [6].

Methodology

The proposed methodology contains seven sequential steps. It is designed to be reproduced in MATLAB/Simulink, LabVIEW or another numerical environment, provided that the same continuous-time motor equations, sampling time, controller constraints and test inputs are maintained.



Common plant, identical reference input and load-disturbance test

Figure 1. Step-by-step methodology used for the PID-FLC comparative study.

Step 1 - DC Motor Mathematical Model

The armature-controlled DC motor is represented by the electrical and mechanical equations $L_a(di_a/dt) = v_a - R_a i_a - K_e \omega$ and $J(d\omega/dt) = K_t i_a - b \omega - T_L$. Here v_a is armature voltage, i_a is armature current, ω is shaft speed and T_L is the external load torque. The parameter set in Table 1 is a compact

benchmark chosen for a 24 V low-power drive. The same model is used for both controllers, preventing plant mismatch from biasing the comparison. Saturation is imposed at ± 24 V to reflect a bidirectional PWM/H-bridge drive; actuator limitation is important because saturation can significantly alter the apparent quality of a controller [4].

Table 1. DC motor parameters used for the reproducible simulation.

Parameter	Symbol	Value	Unit
Armature resistance	R_a	1.2	ohm
Armature inductance	L_a	0.05	H
Torque/back-emf constant	$K_t = K_e$	0.07	N m/A, V s/rad
Rotor inertia	J	0.002	kg m ²
Viscous friction	b	0.002	N m s/rad
Voltage limit	V_{max}	+/- 24	V

Step 2 - PID Controller Design

The continuous PID law is $u(t) = K_p e(t) + K_i \int e(t) dt + K_d de(t)/dt$, where $e(t) = \omega_{ref} - \omega$. For the baseline simulation the gains are $K_p = 0.8$, $K_i = 8.0$ and $K_d = 0.002$. A first-order numerical filter is applied to the derivative term and conditional integration is used to prevent windup when the voltage command reaches its limit. These provisions are consistent with the practical implementation concerns associated with PID control [4]. The gains are selected to provide a stable nominal response before applying the common disturbance test rather than being tuned separately for each test case.

Step 3 - Fuzzy Logic Controller Design

The FLC uses two inputs: normalized speed error $e_n = G_e e$ and normalized change of error $de_n = G_{de} de/dt$. Five triangular linguistic sets are defined on $[-1, 1]$: negative big (NB), negative small (NS), zero (Z), positive small (PS) and positive big (PB). A 25-rule Mamdani-type rule base maps the two inputs to a normalized incremental control command. The scaling factors used in the illustrative simulation are $G_e = 0.01$, $G_{de} = 0.002$ and output increment $G_u = 0.12$ V per 1 ms sample. The rule philosophy follows the classical fuzzy-control principle established by Mamdani-type linguistic synthesis [2] and the motor-control implementations described in [3], [8], and [11].

Table 2. Five-level fuzzy rule base for incremental voltage control.

e / de	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	NS
NS	NB	NB	NS	Z	Z
Z	NS	NS	Z	PS	PS
PS	Z	Z	PS	PB	PB
PB	PS	PS	PB	PB	PB

Step 4 - Common Test Conditions

Both controllers operate with a sampling period of 1 ms. The speed reference is stepped from 0 to 100 rad/s at $t = 0$ s. At $t = 1.5$ s, a 0.10 N m load torque is applied and maintained until the end of the 3 s simulation. No controller is allowed to use a different reference prefilter, supply limit or motor parameter set. This common-condition rule is essential because otherwise a difference in measured response could result from test configuration rather than control law.

Step 5 - Performance Indices

The comparison uses five primary time-domain indices: 10-90% rise time, 2% settling time, peak percentage overshoot, steady-state speed error, and post-disturbance recovery time. A sixth indicator, maximum percentage speed dip after application of load torque, quantifies disturbance sensitivity. These measures are commonly used in comparative motor-control studies because they separate tracking speed, damping, final accuracy and disturbance rejection [9], [10], [12].

Step 6 - Simulation Procedure

The motor states are initialized at zero speed and zero armature current. At each sample the controller receives the current speed error, calculates a voltage command, and passes the command through the common saturation block. The motor differential equations are then integrated to obtain current and speed for the next sample. The full procedure is first executed with PID gains fixed at their selected values and then repeated with the fuzzy controller. Controller output, speed response and load-torque event are logged for the same time vector.

Step 7 - Comparative Decision Rule

The controller with the smaller value of an individual metric is considered better only for that metric. The final conclusion is based on the pattern across all indices. A controller that is faster but produces larger overshoot, for example, should not be declared globally superior unless the application prioritizes response time. This multi-index decision rule prevents overgeneralization and is consistent with the fact that PID, fuzzy and hybrid control

designs optimize different aspects of drive behavior [6], [12].

Results

Figure 2 and Table 3 summarize the illustrative simulation generated from the methodology above. These values are not claimed as physical

laboratory measurements; they are numerical results from the stated motor equations, controller settings and 1 ms integration step. The response shows that both controllers track the 100 rad/s command with negligible final error, but their transient behavior is different.

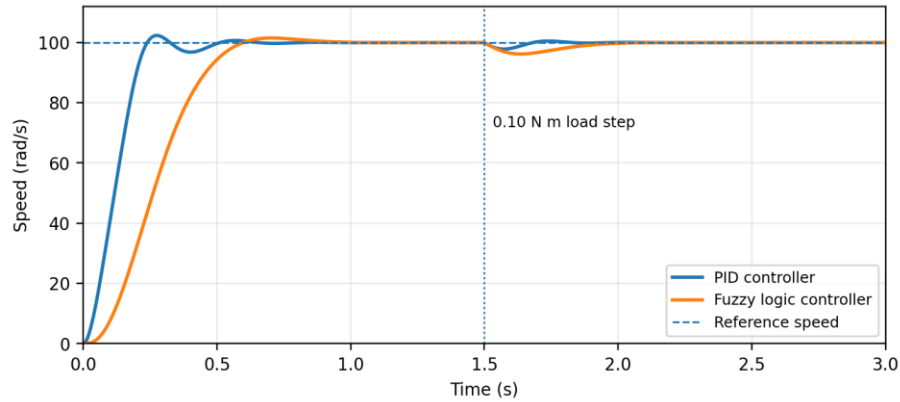


Figure 2. Simulated speed responses; the dotted vertical marker denotes the applied load torque.

Table 3. Performance comparison for the stated nominal simulation and 0.10 N m load step.

Performance index	PID	Fuzzy logic	Lower value
Rise time (s)	0.159	0.344	PID
Settling time, 2% (s)	0.455	0.553	PID
Peak overshoot (%)	2.33	1.51	FLC
Steady-state error (%)	0.001	0.001	Comparable
Load-induced speed dip (%)	2.18	3.83	PID
Disturbance recovery (s)	0.097	0.291	PID

The PID controller reaches 90% of the demanded speed earlier and settles approximately 0.10 s sooner than the FLC. Its maximum load-induced speed reduction is also smaller and recovery is faster. In this particular nominal model, fixed PID gains therefore provide the strongest response-speed and disturbance-rejection performance. The result is plausible because the PID gains were selected directly for the same linear motor dynamics, and similar studies have shown that properly tuned PID can be highly effective for DC speed control [7], [9], [10].

The FLC, however, reduces peak overshoot from approximately 2.33% to 1.51%. More importantly from a methodology perspective, its control action is defined by error/change-of-error rules and scaling rather than by an exact transfer-function design. This model-light characteristic is one reason fuzzy approaches have been repeatedly proposed for DC motor regulation [3], [8], [11]. Thus, the numerical result should be interpreted as a trade-off: PID is preferable for the selected nominal plant when rapid tracking and load recovery dominate, whereas FLC is attractive when reduced

overshoot, linguistic design and potential adaptability to poorly modeled operating conditions are more important. The conclusion is consistent with comparative literature showing that no single controller architecture dominates every index and that intelligent or hybrid controllers can be advantageous when uncertainty increases [6], [12].

Conclusion and Discussion

A step-by-step methodology has been developed for comparing PID and fuzzy logic controllers for DC motor speed regulation under identical plant and disturbance conditions. The study begins with an electromechanical motor model, designs a fixed-gain PID controller and a five-level Mamdani-type FLC, imposes equal voltage saturation, and evaluates both using rise time, settling time, overshoot, steady-state error and disturbance metrics. The illustrative simulation shows a faster nominal response for PID and lower overshoot for FLC. This outcome demonstrates why comparative studies should report multiple performance indices instead of describing one controller as universally better.

For practical application, the choice can therefore be matched to system priorities. PID is appropriate when a sufficiently accurate motor model or repeatable tuning procedure is available and when fast settling and load recovery are dominant. FLC becomes attractive when expert rules are easier to obtain than accurate parameters, when nonlinear operating regions are significant, or when controller adaptability is required. A logical extension is to repeat the same procedure under resistance, inertia and friction uncertainty and then test a fuzzy-PID hybrid; prior adaptive fuzzy-PID work suggests that such combinations can retain PID accuracy while adding online adaptability [6]. Hardware-in-the-loop or encoder-based experimental validation should be performed before making claims about real-time implementation performance.

Interpretation of the Controller Trade-off

The numerical comparison also illustrates an important methodological point: a lower overshoot does not automatically imply a better overall regulator, just as a shorter rise time does not automatically imply better robustness. In the selected fuzzy rule base, the controller progressively changes the applied voltage as the error and error derivative move among linguistic regions. This produces a comparatively smooth approach to the reference and reduces peak overshoot, but it also delays the aggressive corrective action needed after the load torque is introduced. The fixed PID controller, by contrast, has a strong integral contribution and a proportional gain selected around the nominal plant; it therefore restores speed quickly after the disturbance but allows a slightly larger initial peak. The same trade-off has motivated adaptive and hybrid fuzzy-PID structures in the literature, where fuzzy inference modifies PID action when the operating point changes [6].

For applications such as conveyor drives, machine-tool feed systems or laboratory actuators operating around a well-defined nominal point, a carefully tuned PID may therefore be the economical choice because implementation and maintenance are straightforward. When motor parameters vary with temperature, load inertia changes frequently, or nonlinear effects such as dead zones and friction become dominant, a rule-based controller may justify its additional design effort. The comparative procedure in this paper supports either decision because it reports the separate effects on transient tracking and disturbance rejection rather than combining all outcomes into an arbitrary single score. If a weighted score is required, the weights should be

selected from application requirements before controller tuning so that the evaluation criterion is not adjusted after the results are known.

Limitations and Reproducibility Considerations

The present results are intentionally limited to a deterministic simulation and should be interpreted within that scope. The motor model neglects brush voltage drop, Coulomb friction, PWM switching ripple, encoder quantization, current-loop dynamics, measurement noise and thermal variation of armature resistance. The FLC is also represented by one five-level rule base and one set of scaling factors; different membership shapes, a seven-level partition or optimization of the rule base could change its ranking. Similarly, alternate PID tuning criteria could reduce overshoot or increase disturbance rejection. These limitations do not invalidate the methodology; instead, they identify the variables that should be changed systematically in a more extensive study.

Reproducibility requires reporting the motor parameters, controller gains, fuzzy membership ranges, rule matrix, sample time, voltage saturation, reference profile and load disturbance exactly as done here. A follow-up experimental study should use the same definitions of rise time, settling band and recovery time, because inconsistent definitions can create misleading comparisons even when the raw speed traces are similar. Repeating each hardware test over several runs and reporting mean and variation would separate controller behavior from sensor noise and mechanical repeatability. The literature up to 2016 provides a strong basis for such validation: real-time fuzzy and adaptive fuzzy implementation has already been demonstrated [8], [13], conventional and fuzzy controllers have been compared in simulation [9], [11], and intelligent controllers have been benchmarked against PID for DC motor speed regulation [12].

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