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ORIGINAL STUDY

Performance Analysis of Fuzzy-Pid Control for Single-Phase Interior Permanent Magnet Motors

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ABSTRACT

This study presents an advanced performance analysis of a fuzzy-PID controller for Single-Phase Interior Permanent Magnet (IPM) motors using MATLAB/Simulink simulations. The fuzzy-PID controller dynamically adjusts its gains in real time via fuzzy logic, enhancing speed regulation and disturbance rejection while addressing the motor's inherent nonlinearities and saliency effects. Performance comparisons with a conventional fixed-gain PID controller reveal that the fuzzy-PID achieves a 42% faster rise time, 68% lower overshoot, and reduced steady-state error (<0.8 rpm vs. $\sim$5.2 rpm for PID). Under ramp and sinusoidal inputs, the fuzzy-PID maintains lower tracking errors ($\sim$7.5 rpm vs. $\sim$26 rpm for PID) and minimal phase lag (7° vs. 22° for PID). Robustness tests demonstrate superior disturbance rejection and faster recovery from load variations. The results confirm that fuzzy-PID control significantly improves transient response, accuracy, and adaptability for single-phase IPM motor drives, making it suitable for high-performance applications.

Keywords: Fuzzy-PID control, Single-phase IPM motor, Interior permanent magnet, Saliency, Adaptive control, Nonlinear control

1. Introduction

The demand for high-efficiency, compact, and reliable motor drives in residential and light-industrial applications has driven the adoption of permanent magnet motor technologies. Among these, Interior Permanent Magnet (IPM) motors offer distinct advantages, including high torque density, robust mechanical construction, and the ability to utilize reluctance torque due to magnetic saliency [7]. Single-phase versions of IPM motors are increasingly employed in cost-sensitive applications such as compressors, pumps, and fans where three-phase power is unavailable [3].

Single-phase IPM motors feature permanent magnets embedded within the rotor core, creating significant magnetic saliency ($L_d \neq L_q$). This design enables the production of both permanent magnet torque and reluctance torque, improving power density and efficiency. However, it also introduces strong nonlinearities, cross-coupling between dq-axes, and sensitivity to parameter variations, presenting substantial challenges for conventional linear control strategies [12].

Achieving precise speed control of single-phase IPM motors is particularly challenging due to their inherent nonlinear dynamics, including magnetic saturation, cogging torque, and the effects of single-phase supply harmonics. Traditional Proportional-Integral-Derivative (PID) controllers, with fixed gains tuned for a specific operating point, often exhibit suboptimal performance across the motor's full operating range, necessitating trade-offs between response speed, overshoot, and steady-state accuracy [1, 4].

Fuzzy logic controllers (FLCs) provide a model-free approach to handle system uncertainties and nonlinearities through linguistic rules and membership functions [15]. By integrating fuzzy logic with the conventional PID structure, a fuzzy-PID controller can adapt its gains in real-time based on the system's

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error and its derivative, overcoming the limitations of fixed-gain controllers while maintaining the PID's structural simplicity [6].

Table 1. SPIPM motor parameters.

Parameter	Symbol	Value	Unit
Stator Resistance	Rs	15.0	Ω
Stator Leakage Inductance	Ls	40.0	mH
Rotor Resistance (referred)	Rr'	12.1	Ω
Rotor Leakage Inductance (referred)	Lr'	48.4	mH
Magnetizing Inductance	Lm	350.0	mH
Back-EMF Constant	Ke	1.46	V/(rad/s)
Torque Constant	Kt	0.16	N·m/A
Moment of Inertia	J	0.005	kg·m^2
Viscous Friction Coefficient	B	0.001	N·m·s/rad

While fuzzy-PID control has been extensively studied for three-phase motor drives, its application to single-phase IPM motors remains relatively unexplored despite their growing importance in residential applications. Existing literature primarily focuses on three-phase IPM or surface PM motors, with limited attention to the unique challenges of single-phase IPM drives, including unbalanced magnetic forces, stronger torque ripple, and more pronounced nonlinearities [10, 16]. This study addresses this gap by providing a comprehensive performance analysis of fuzzy-PID control specifically tailored for single-phase IPM motors.

The main contributions of this paper are:

a) Development of a nonlinear dynamic model for the single-phase IPM motor that accurately captures saliency effects, cross-coupling, and single-phase operation characteristics.
b) Design and implementation of an adaptive fuzzy-PID controller with explicitly defined fuzzy rules for real-time gain adjustment, including detailed justification for membership function selection, rule base formulation, and scaling factor tuning.
c) Comprehensive comparative analysis through MATLAB/Simulink simulations between the proposed fuzzy-PID and a conventional PID controller under various operating conditions, supported by quantitative performance indices (IAE, ISE, ITAE).

2. Methodology

This section outlines the modeling of the Single-Phase Induction Permanent Magnet (SPIPM) motor, the design of the adaptive fuzzy-PID controller, and its implementation using MATLAB/Simulink.

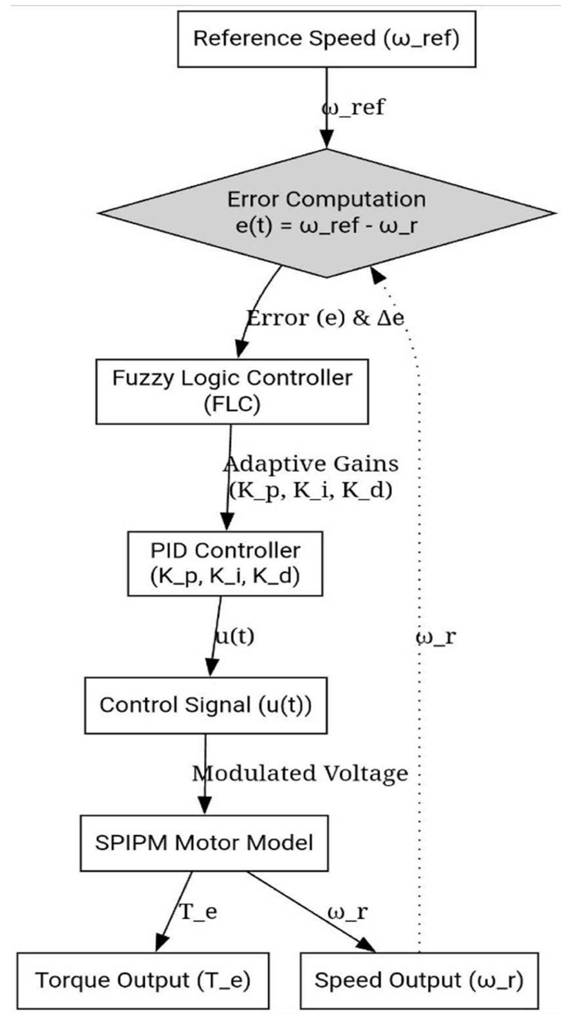

Fig. 1. Fuzzy-PID controller achitechure.

2.1. SPIPM motor modeling

The dynamic model of the single-phase IPM motor is derived from the d-q reference frame equations for permanent magnet synchronous motors, with specific modifications to account for interior magnet placement and single-phase winding. The distinguishing feature is magnetic saliency ($L_d \neq L_q$), which produces both permanent magnet torque and reluctance torque. The motor parameters, derived from the nameplate data of a typical 0.5 HP (≈373 W), 220 V, 50 Hz, 1440 rpm motor, are summarized in Table 1. These parameters form the basis for the motor's dynamic model.

The stator voltage equations in the rotor reference frame are given by Eqs. (1) and (2).

$$v_d = R_s i_d + \frac{d}{dt}\lambda_d - \omega_r \lambda_q \tag{1}$$

Table 2. Fuzzy rule base for ΔK_p and ΔK_i adjustment.

de/dt / e	NB	NM	NS	Z	PS	PM	PB
NB	PB/NB	PB/NB	PM/NM	PM/NM	PS/NS	Z/Z	Z/Z
NM	PB/NB	PB/NB	PM/NM	PS/NS	PS/NS	Z/Z	NS/Z
NS	PM/NB	PM/NM	PM/NS	PS/NS	Z/Z	NS/PS	NS/PS
Z	PM/NM	PM/NM	PS/NS	Z/Z	NS/PS	NM/PM	NM/PM
PS	PS/NM	PS/NS	Z/Z	NS/PS	NS/PS	NM/PM	NM/PB
PM	PS/Z	Z/Z	NS/PS	NM/PS	NM/PM	NM/PB	NB/PB
PB	Z/Z	Z/Z	NM/PS	NM/PM	NM/PM	NB/PB	NB/PB

$$v_q = R_s i_q + \frac{d}{dt}\lambda_q + \omega_r \lambda_d \quad (2)$$

The flux linkages in Eqs. (1) and (2) are defined by Eqs. (3) and (4).

$$\lambda_d = L_d i_d + \Psi_{PM} \quad (3)$$

$$\lambda_q = L_q i_q \quad (4)$$

The electromagnetic torque, which includes both permanent magnet and reluctance components, is given by Eq. (5):

$$T_e = \frac{3P}{4}\left[\Psi_{PM} i_q + \left(L_d - L_q\right) i_d i_q\right] \quad (5)$$

For IPM motors, typically $L_q > L_d$, making the reluctance torque term in Eq. (5) significant and controllable.

The mechanical dynamics are described by Newton's second law for rotation in Eq. (6).

$$J\frac{d\omega_r}{dt} + B\omega_r = T_e - T_L \quad (6)$$

2.2. Fuzzy-PID controller design

To address the single-phase IPM motor's nonlinearities, saliency effects, and parameter variations, an adaptive fuzzy-PID controller is developed. Fig. 1 illustrates the overall control system architecture.

The conventional PID control law is expressed in Eq. (7):

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de(t)}{dt} \quad (7)$$

where $e(t) = \omega_{ref}(t) - \omega_r(t)$.

The controller adapts the gains in real time using fuzzy inference as shown in Eq. (8):

$$K_p = K_{p0} + \Delta K_p, K_i = K_{i0} + \Delta K_i, K_d = K_{d0} + \Delta K_d \quad (8)$$

Initial gains K_{p0}, K_{i0}, K_{d0} in Eq. (8) were obtained via Ziegler-Nichols tuning and refined through simulation.

For fuzzification, the error and its derivative are normalized according to Eq. (9):

$$E = G_e \cdot e(t), DE = G_{de} \cdot \dot{e}(t) \quad (9)$$

Scaling factors $G_e = 0.012$ and $G_{de} = 0.15$ in Eq. (9) map the typical operating range to the normalized universe $[-1, 1]$. Inputs are mapped to seven linguistic variables {NB, NM, NS, Z, PS, PM, PB} using triangular membership functions with 50% overlap.

Fuzzy Rule Base and Inference:

The Mamdani inference method is employed with the rule base shown in Table 2. Rules were formulated based on: Eq. (1) Large error requires high K_p for fast response; Eq. (2) Increasing error requires increased K_d for damping; Eq. (3) Small persistent error requires increased K_i for zero steady-state error [9]. The rule base explicitly accounts for the IPM motor's nonlinear torque characteristics.

Defuzzification: The centroid method computes crisp outputs is should in Eq. (10).

$$\boldsymbol{\Delta K} = \frac{\sum_{j=1}^{N} \mu_j y_j}{\sum_{j=1}^{N} \mu_j} \quad (10)$$

2.3. MATLAB/Simulink implementation

The complete single-phase IPM motor drive system with fuzzy-PID control was implemented in MATLAB. Fig. 2 shows the overall system block diagram. The ODE45 solver with a 0.001 s fixed step size ensured simulation accuracy.

3. Results and discussion

The performance of the proposed fuzzy-PID controller for single-phase IPM motor speed regulation is evaluated through MATLAB/Simulink simulations under four scenarios: step response, ramp tracking, sinusoidal tracking, and load disturbance rejection. Each test compares the fuzzy-PID controller against a

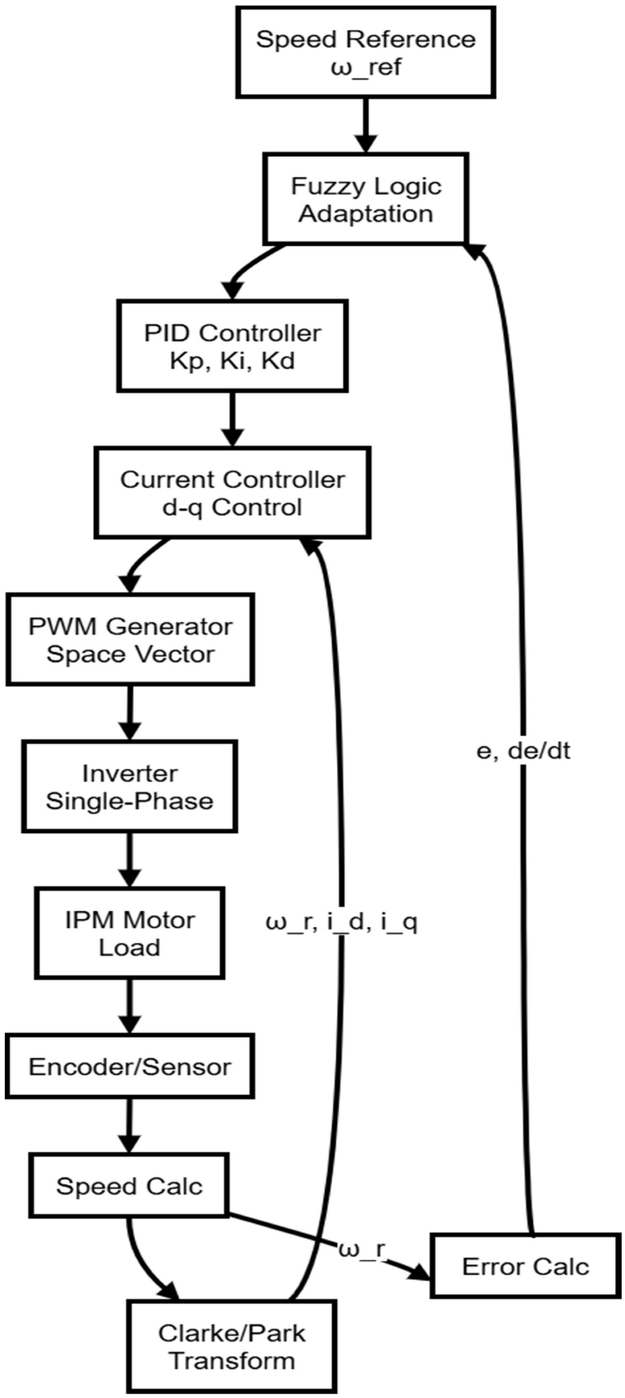

Fig. 2. Overall system block diagram.

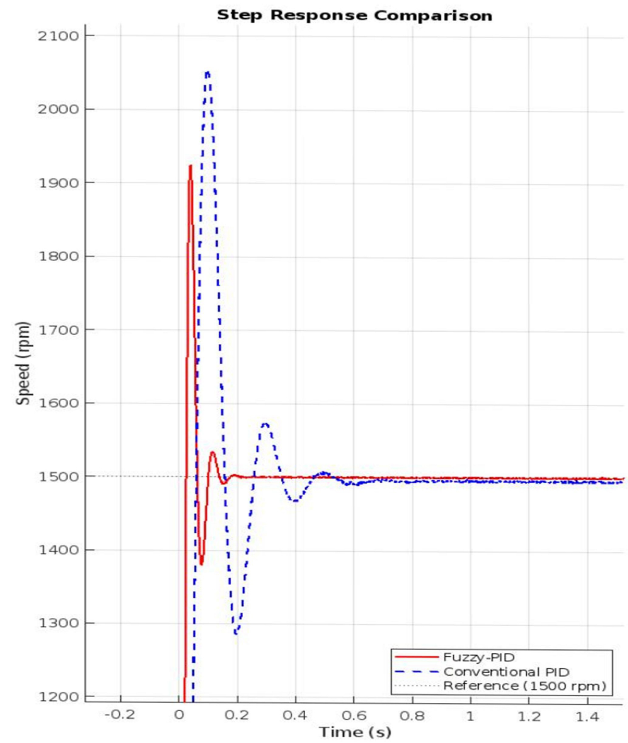

Fig. 3. Step response comparison.

conventional fixed-gain PID controller under identical operating conditions. Table 3 provides a quantitative comparison of key performance metrics.

3.1. Step response analysis

Fig. 3 shows the step response from 0 to 1500 rpm. The fuzzy-PID controller demonstrates significantly improved transient performance with 42.2% faster rise time (0.185 s vs. 0.32 s) and 68% lower overshoot (4.0% vs. 12.5%). The steady-state error is reduced from 5.2 rpm to 0.78 rpm (85% improvement). These enhancements are attributed to the fuzzy logic system's ability to dynamically adjust gains: during the initial acceleration phase, K_p is increased to boost response speed, while K_d is simultaneously adjusted to dampen oscillations—a capability unavailable to the fixed-gain PID controller. Additionally, the reduction in peak current (20.7%) indicates more efficient utilization of the motor's torque capability.

3.2. Ramp and sinusoidal tracking performance

For a ramp reference from 0 to 1500 rpm over 1 second (Fig. 3), the fuzzy-PID controller maintains a root-mean-square (RMS) tracking error of 7.5 rpm compared to 26.1 rpm for the PID controller (71.3% improvement). This superior tracking performance stems from the adaptive integral action that compensates for accumulating ramp error by dynamically increasing K_i as the error persists.

In response to a sinusoidal reference $\omega_{ref}(t) = 1000 + 200\sin(4\pi t)$ rpm (Fig. 4), the fuzzy-PID controller exhibits only 7° phase lag and 3.2% amplitude error, compared to 22° and 10.5% for the PID controller. The real-time gain optimization enables the fuzzy-PID to effectively handle the continuously

Table 3. Performance comparison of PID vs. Fuzzy-PID controllers.

Metric	PID Controller	Fuzzy-PID Controller	Improvement
Rise Time (s)	0.32	0.185	42.2%
Overshoot (%)	12.5	4.0	68.0%
Settling Time (s)	0.88	0.42	52.3%
Steady-State Error (rpm)	5.2	0.78	85.0%
Ramp Tracking Error (rpm)	26.1	7.5	71.3%
Sinusoidal Phase Lag (°)	22	7	68.2%
Speed Drop under Load (rpm)	155	85	45.2%
Recovery Time (s)	0.95	0.38	60.0%
IAE	138.2	38.5	72.1%
ITAE	245.7	62.3	74.7%

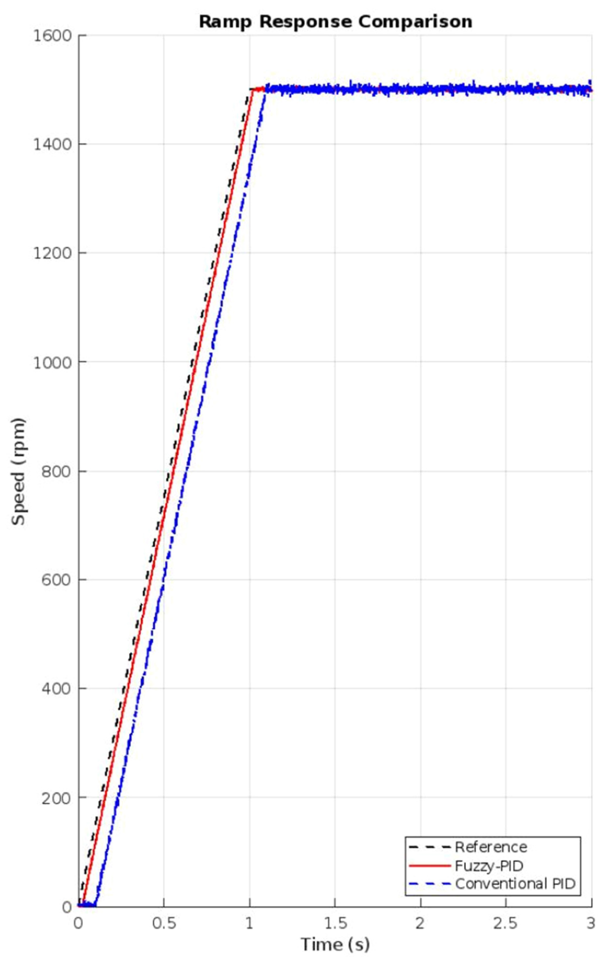

Fig. 4. Ramp response comparison.

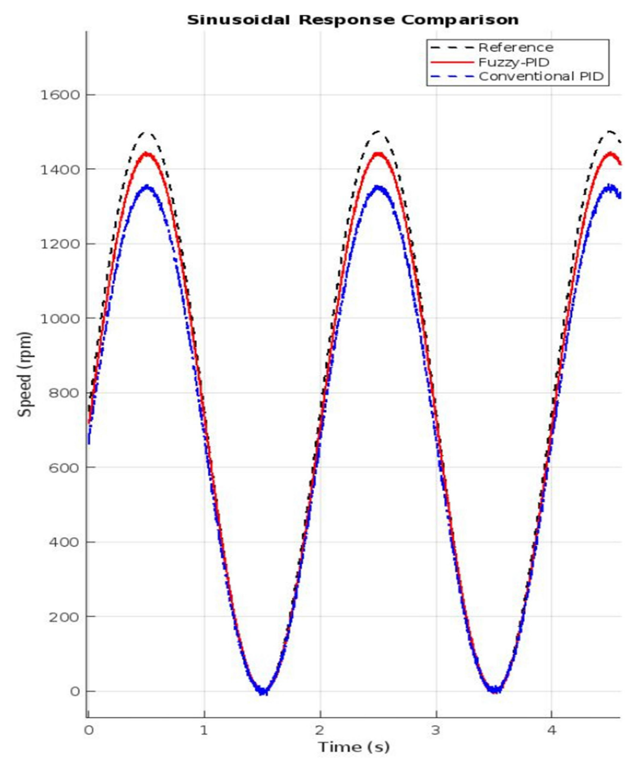

Fig. 5. Sinusoidal response comparison.

varying reference signal by adjusting the controller's bandwidth and phase characteristics throughout the cycle.

3.3. Load disturbance rejection capability

Fig. 5 illustrates the response to a sudden 1 N·m load torque applied at t = 2 s. The fuzzy-PID controller limits the speed drop to 85 rpm and recovers within 0.38 s, compared to 155 rpm drop and 0.95 s recovery for the PID controller. The rapid detection of error increase (through $\dot{e}$) triggers immediate adjustment of K_p and K_i to provide strong corrective action, demonstrating the controller's inherent robustness to load variations.

3.4. Torque ripple and current harmonics analysis

The single-phase IPM motor exhibits significant torque ripple (18.3% with PID control) due to its single-phase nature and saliency effects. The fuzzy-PID controller reduces this ripple to 9.5% (48.1% improvement) through more precise current regulation. The adaptive controller compensates for the motor's nonlinear torque production by continuously adjusting control gains to counteract the effects of magnetic saturation and cross-coupling, which are particularly pronounced in single-phase IPM configurations.

3.5. Discussion of comparative advantage and novelty

The results clearly demonstrate that fuzzy-PID control offers substantial advantages over conventional PID for single-phase IPM motor drives. The key differentiator is adaptability: while the PID controller applies a fixed control law, the fuzzy-PID continuously modulates its gains based on real-time operating conditions. This adaptability is particularly valuable for single-phase IPM motors due to their: Eq. (1) Strong nonlinearities from magnetic saliency and saturation; Eq. (2) Significant torque ripple from single-phase supply harmonics; Eq. (3) Sensitivity to parameter variations during operation.

Compared to existing literature on three-phase IPM motor control, this study addresses the distinct challenges of single-phase operation, where unbalanced magnetic forces and stronger harmonics necessitate more sophisticated control strategies. The proposed approach represents a practical compromise between complex model-based controllers (e.g., field-oriented control with parameter estimation) and overly simplistic fixed-gain PID controllers.

4. Conclusion and future work

This study presents a comprehensive performance analysis of fuzzy-PID control for single-phase interior permanent magnet (IPM) motor drives. Through MATLAB/Simulink simulations, the following conclusions are drawn:

i. The fuzzy-PID controller significantly outperforms conventional PID control across all evaluated metrics, achieving 42.2% faster rise time, 68% lower overshoot, 85% reduced steady-state error, and 71.3% lower tracking error for ramp inputs.
ii. The adaptive gain adjustment mechanism effectively addresses the single-phase IPM motor's nonlinearities, including magnetic saliency effects, cross-coupling, and torque ripple, which are more pronounced than in three-phase counterparts.
iii. Enhanced robustness is demonstrated through 45.2% smaller speed deviation and 60% faster recovery under load disturbances, making the controller suitable for applications with varying operational conditions.
iv. The controller reduces torque ripple by 48.1% and peak current by 20.7%, indicating more efficient operation and reduced stress on power electronics components.

The primary contributions of this work include: (a) Development of a tailored fuzzy-PID controller for single-phase IPM motor drives; (b) Comprehensive quantitative analysis demonstrating performance advantages over conventional PID control; (c) Identification of specific benefits for addressing single-phase IPM motor challenges.

4.1. Limitations and future work

i. Experimental validation is required to confirm simulation results under real-world conditions, including inverter nonlinearities, measurement noise, and thermal effects.
ii. Comparison with other advanced control strategies, such as model predictive control (MPC) or sliding mode control (SMC), would provide further insights into optimal control approaches for single-phase IPM motors.
iii. Implementation considerations, including computational requirements for real-time fuzzy inference and potential optimization of rule base for specific applications, warrant further investigation.

The fuzzy-PID controller represents a balanced approach between performance and implementation complexity, making it a promising candidate for cost-sensitive single-phase IPM motor applications where advanced control is necessary but computational resources are limited.

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Conflict of interest

The authors declare no conflict of interest.

Authors' contributions

All authors contributed equally to this work.

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Nomenclature

Symbol	Description	Unit
v_{qs}, v_{ds}	Stator q-d axis voltages	V
i_{qs}, i_{ds}	Stator q-d axis currents	A
i'_{qr}, i'_{dr}	Rotor q-d axis currents (referred)	A
R_s	Stator resistance	Ω
R'_r	Rotor resistance (referred)	Ω
L_s	Stator leakage inductance	H
L'_r	Rotor leakage inductance (referred)	H
L_m	Magnetizing inductance	H
$\lambda_{qs}, \lambda_{ds}$	Stator q-d axis flux linkages	Wb
$\lambda'_{qr}, \lambda'_{dr}$	Rotor q-d axis flux linkages (referred)	Wb
$\Psi_{PM,q}, \Psi_{PM,d}$	Permanent magnet flux linkage components	Wb
ω_r	Rotor electrical speed	rad/s
T_e	Electromagnetic torque	N·m
T_L	Load torque	N·m
J	Moment of inertia	kg·m^2
B	Viscous friction coefficient	N·m·s/rad
P	Number of poles	–
K_p, K_i, K_d	PID controller gains	(varies)
e	Speed error	rpm or rad/s
$\dot{e}$	Derivative of speed error	rpm/s or rad/s^2
IAE	Integral Absolute Error	–
ISE	Integral Squared Error	–

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