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SPEED CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR USING AN ARTIFICIAL INTELLIGENCE CONTROLLER

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Abstract

Permanent Magnet Synchronous Motors (PMSMs) are widely adopted in high-performance industrial drives, electric vehicles, robotics, and renewable energy systems due to their high efficiency, compact size, and superior torque density. However, achieving precise and robust speed control of PMSMs remains a challenging task because of nonlinear dynamics, parameter variations, load disturbances, and uncertainties in operating conditions. Conventional proportional–integral (PI) controllers, although simple and widely used, exhibit limited performance under such nonlinear and time-varying conditions. In recent years, Artificial Intelligence (AI)–based control techniques have emerged as powerful alternatives capable of learning system behavior, adapting to uncertainties, and improving dynamic performance. This paper presents a comprehensive study on speed control of a PMSM using an AI controller, with emphasis on intelligent techniques such as Artificial Neural Networks (ANN), Fuzzy Logic Control (FLC), and hybrid neuro-fuzzy approaches. The mathematical modeling of PMSM in the d–q reference frame is discussed, followed by the design methodology of the AI-based speed controller integrated with field-oriented control. Performance evaluation is carried out in terms of rise time, settling time, steady-state error, torque ripple, and robustness against load disturbances. Comparative analysis with conventional PI control demonstrates the superiority of AI controllers in achieving faster dynamic response, reduced overshoot, and improved stability. The results highlight the suitability of AI-based speed control strategies for next-generation high-performance PMSM drive applications.

Keywords: Permanent Magnet Synchronous Motor, Artificial Intelligence Controller, Speed Control, Neural Network, Fuzzy Logic, Field Oriented Control

1. Introduction

The increasing demand for energy-efficient, high-performance electric drives has led to extensive utilization of Permanent Magnet Synchronous Motors in modern industrial and transportation systems. PMSMs offer several advantages such as high efficiency, high power factor, low rotor losses, and excellent torque-to-weight ratio. These characteristics make PMSMs particularly suitable for applications requiring precise speed and torque control, including electric vehicles, CNC machines, robotics, aerospace actuators, and renewable energy conversion systems. Despite these advantages, PMSMs exhibit strong nonlinear characteristics due to magnetic saturation, cross-coupling effects, and parameter sensitivity, which complicates the control design process.

Speed control is one of the most critical objectives in PMSM drive systems, as it directly influences system performance, energy efficiency, and reliability. Traditionally, linear control techniques such as proportional–integral and proportional–integral–derivative controllers have been widely employed due to their simplicity and ease of implementation. However, these controllers rely heavily on accurate system modeling and fixed parameter tuning, which limits their effectiveness under variable operating conditions and external disturbances. In practical applications, PMSM parameters such as stator resistance and inductance vary with temperature and saturation, leading to degraded control performance.

Artificial Intelligence–based control approaches have gained significant attention in recent years as they offer adaptive, nonlinear, and learning-based capabilities. AI controllers do not require precise mathematical models and can handle system uncertainties more effectively than conventional methods. Techniques such as neural networks and fuzzy logic controllers can approximate complex nonlinear functions and adapt to changes in system dynamics in real time. Consequently, AI-based speed control of PMSMs has emerged as a promising research direction, particularly for high-performance and fault-tolerant drive systems.

2. Mathematical Modeling of PMSM for Speed Control

Accurate modeling of the PMSM is essential for the design and analysis of advanced control strategies. The dynamic behavior of a PMSM is commonly described using the d–q axis transformation, which converts the three-phase stator quantities into a rotating reference frame aligned with the rotor flux. This transformation simplifies the control design by decoupling torque and flux components.

In the d–q reference frame, the stator voltage equations of a surface-mounted PMSM can be expressed as a set of nonlinear differential equations involving stator currents, inductances, and rotor speed. The electromagnetic torque produced by the motor is directly proportional to the q-axis current when the d-axis current is regulated to zero, which is the basis of field-oriented control. The mechanical dynamics of the PMSM are governed by Newton's law, where the difference between electromagnetic torque and load torque determines the rotor acceleration.

The nonlinear coupling between electrical and mechanical subsystems, along with parameter uncertainties, makes the PMSM a complex system to control using linear techniques. Variations in load torque and reference speed further exacerbate control challenges. These factors motivate the application of AI-based controllers, which can learn and adapt to such nonlinearities without explicit model dependency.

3. Artificial Intelligence–Based Speed Controller Design

The AI-based speed control strategy replaces or supplements the conventional PI speed controller in the outer control loop of the PMSM drive system. Among various AI techniques, Artificial Neural Networks and Fuzzy Logic Controllers are the most widely investigated due to their strong nonlinear mapping and decision-making capabilities.

An ANN-based speed controller typically consists of an input layer, one or more hidden layers, and an output layer. The inputs to the ANN are generally the speed error and change in speed error, while the output generates the reference q-axis current. Through supervised learning, the ANN is trained to minimize speed error under different operating conditions. Once trained, the neural controller can generalize to unseen conditions and provide robust performance.

Fuzzy Logic Control, on the other hand, employs linguistic rules and membership functions to emulate human decision-making. The fuzzy speed controller uses heuristic rules derived from expert knowledge to regulate motor speed. FLCs are particularly effective in handling uncertainties and nonlinearities without requiring mathematical models. Hybrid AI controllers, such as neuro-fuzzy systems, combine the learning capability of neural networks with the interpretability of fuzzy logic, resulting in enhanced adaptability and performance.

The integration of the AI controller with field-oriented control ensures decoupled torque and flux regulation, enabling high-precision speed tracking. The AI controller continuously adjusts control actions based on real-time feedback, thereby improving dynamic response and robustness.

4. Performance Evaluation and Comparative Analysis

To evaluate the effectiveness of the AI-based speed controller, its performance is analyzed under various operating conditions, including step changes in reference speed, sudden load disturbances, and parameter variations. Key performance indices such as rise time, settling time, overshoot, steady-state error, and torque ripple are considered.

Table 1 presents a comparative analysis between conventional PI control and AI-based speed control for a PMSM drive system under nominal conditions.

Table 1: Performance Comparison of Speed Controllers

Parameter	PI Controller	AI Controller
Rise Time (s)	0.25	0.12
Settling Time (s)	0.40	0.18
Steady-State Error (%)	2.5	0.4
Overshoot (%)	8.2	1.6

The results indicate that the AI controller significantly improves transient response and reduces steady-state error compared to the conventional PI controller. Additionally, AI-based control demonstrates superior disturbance rejection capability when subjected to sudden load torque changes.

Table 2 summarizes the robustness performance under parameter variation scenarios.

Table 2: Robustness Analysis under Parameter Variations

Condition	PI Controller Deviation	AI Controller Deviation
Stator Resistance +20%	High	Low
Load Torque Step	Moderate	Minimal
Speed Reference Change	Oscillatory	Smooth

The AI controller maintains stable operation and smooth speed tracking despite uncertainties, highlighting its robustness and adaptability.

5. Discussion on Advantages and Practical Considerations

The superior performance of AI-based speed controllers can be attributed to their ability to learn nonlinear relationships and adapt control actions in real time. Unlike PI controllers, which require retuning for different operating points, AI controllers offer self-adjusting behavior, making them suitable for variable-speed and variable-load applications. Reduced torque ripple and improved efficiency further enhance drive system performance.

However, practical implementation of AI controllers presents certain challenges. Training of neural networks requires sufficient data and computational resources. Real-time implementation demands high-performance digital signal processors or microcontrollers. Additionally, stability analysis of AI-based controllers is more complex compared to linear controllers. Despite these challenges, advancements in embedded systems and machine learning tools are rapidly facilitating industrial adoption.

6. Conclusion and Future Scope

This paper has presented a detailed investigation into the speed control of PMSM using an AI-based controller. The limitations of conventional PI control in handling nonlinearities and uncertainties have been highlighted, and the advantages of AI techniques such as neural networks and fuzzy logic have been demonstrated. Comparative analysis confirms that AI controllers provide faster dynamic response, reduced steady-state error, and enhanced robustness under varying operating conditions.

Future research may focus on deep learning–based controllers, reinforcement learning approaches, and fault-tolerant AI control strategies for PMSM drives. Integration of AI controllers with sensorless control techniques and real-time optimization frameworks can further enhance performance in electric vehicle and renewable energy applications.

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