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Comparative Analysis of Control Strategies for BLDC Motors in Unmanned Aerial Vehicle (UAV) Propulsion

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A B S T R A C T

Unmanned Aerial Vehicles (UAVs) depend on advanced motor control systems to maintain high performance and maneuverability. This study examines different control strategies for Brushless DC (BLDC) motors in UAVs, specifically exploring Sliding Mode Control (SMC), Adaptive PID Control, Model Predictive Control (MPC), and Direct Torque Control (DTC). Each control method is analyzed using key performance indicators such as precision, energy efficiency, and response speed, providing insights into their suitability for UAV propulsion applications. With UAVs being increasingly deployed in fields like surveillance, mapping, and agriculture, the findings guide designers in choosing control strategies that maximize efficiency, stability, and adaptability to various operational conditions. The study utilizes simulations and prototype testing to evaluate each strategy's effectiveness, helping UAV designers select approaches that optimize battery life, responsiveness, and adaptability to mission requirements across diverse applications.

Keywords: Unmanned Aerial Vehicles (UAVs), Brushless DC (BLDC) motors, Control strategies, Energy efficiency, Precision, Adaptability

1. Introduction

Unmanned Aerial Vehicles (UAVs) have gained substantial traction across various sectors, from military operations to civilian applications, primarily due to their adaptability and operational simplicity. One of the most critical components influencing UAV performance is the propulsion system, and Brushless DC (BLDC) motors have emerged as a popular choice for UAV propulsion. BLDC motors are highly efficient, require minimal maintenance, and possess an excellent power-to-weight ratio, making them ideal for a wide range of UAV missions, from long-endurance surveillance to rapid-response applications. However, the effectiveness of these motors is closely tied to the control strategy employed, as it directly impacts critical performance factors such as speed, torque, and energy consumption. Optimal control strategies can maximize battery life, enhance stability, and ensure the UAV responds robustly to environmental changes, which is crucial as UAVs become essential tools in modern infrastructure.

The variety of operational demands faced by UAVs has driven the development and evaluation of multiple control methods, each tailored to specific performance needs. Sliding Mode Control (SMC) is recognized for its robustness and quick responsiveness, making it suitable for high-turbulence scenarios. Adaptive PID Control provides smooth control across variable speeds and changing loads, while Model Predictive Control (MPC) is known for its precision and energy efficiency, which is particularly valuable for missions that require battery conservation and long-duration flights. Direct Torque Control (DTC), on the other hand, excels in situations where rapid torque adjustments are necessary, supporting UAVs that encounter frequent speed changes. With UAV applications expanding in areas such as environmental monitoring, precision agriculture, forestry management, and logistics, control systems must be highly adaptable to manage dynamic conditions, including shifts in payload, wind fluctuations, and mission-specific requirements. A comparative analysis of these control strategies is therefore essential to determine the most effective approach for UAV applications based on specific mission needs.

This research aims to provide UAV designers and engineers with practical insights by conducting an in-depth comparison of SMC, Adaptive PID, MPC, and DTC control strategies for BLDC motors. By examining each strategy's strengths and limitations in terms of energy use, adaptability, control precision, and computational requirements, the study highlights how these methods can address various UAV operational demands. Such knowledge is critical for engineers seeking to balance performance demands with energy conservation, enabling the development of UAVs that are not only efficient but also versatile and reliable across diverse applications—from high-stakes military missions requiring robust, rapid responsiveness to eco-friendly civilian tasks that demand stability and energy efficiency. Ultimately, the findings from this analysis support more informed decision-making, guiding UAV engineers in selecting control strategies that maximize UAV efficiency, reliability, and operational range.

2. Objectives

This research is dedicated to evaluating and comparing control strategies for BLDC motors used in UAV propulsion systems, with the objective of making informed recommendations to optimize UAV performance. As UAV technology advances, selecting effective control strategies is crucial for enhancing flight performance, energy efficiency, and stability. This study begins by exploring recent trends in UAV design, focusing on sustainable choices and efficient propulsion systems that improve UAV capabilities. By analyzing these trends, the research underscores the significance of motor control in achieving extended flight times, increased maneuverability, and greater payload capacities, which are essential across a range of applications, from military reconnaissance to commercial deliveries. Specifically, the study examines four control methods—Sliding Mode Control (SMC), Adaptive PID Control, Model Predictive Control (MPC), and Direct Torque Control (DTC)—each with unique advantages and limitations affecting motor performance, energy efficiency, and responsiveness. Through this comparative analysis, the study seeks to clarify how these strategies enable UAVs to adapt to variable flight conditions, optimize battery usage, and ensure operational stability in diverse mission scenarios.

Beyond improving motor performance, a core aim of this research is to investigate how sustainable materials, energy-efficient components, and eco-conscious design principles can support the development of environmentally friendly UAVs. Integrating these sustainable elements with effective motor control aligns with global sustainability objectives and enhances user experience by allowing longer, more stable flights with lower resource demands. By offering actionable insights into control strategies and their impact on energy efficiency and environmental impact, the study provides a framework to guide UAV developers in making strategic decisions that contribute to both performance and sustainability. This approach positions UAVs as versatile, eco-friendly solutions that meet evolving user demands across various fields, advancing their role as reliable tools for applications requiring both endurance and environmental responsibility.

3. Methodology

The methodology for this comparative analysis of BLDC motor control strategies is organized into several stages to enable a thorough evaluation of each approach. It begins with a comprehensive literature review to establish a foundational understanding of the strengths and limitations of four primary control methods for BLDC motors in UAV applications: Sliding Mode Control (SMC), Adaptive PID Control, Model Predictive Control (MPC), and Direct Torque Control (DTC). This review synthesizes insights from recent studies on each method’s energy efficiency, adaptability, response time, and precision, identifying key performance benchmarks and principles that guide the experimental design and contextualize the findings. This initial stage not only defines the theoretical framework for each control strategy but also highlights their potential roles in UAV propulsion, setting the stage for the following simulation and testing phases.

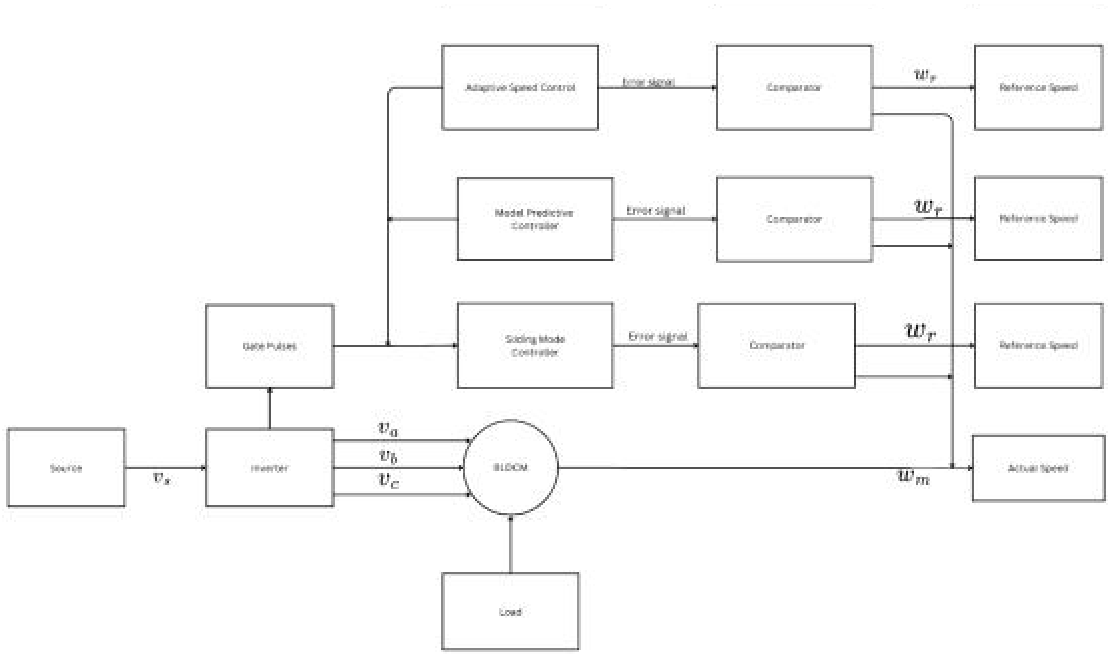

Fig. Block diagram

The block diagram illustrates a control system framework for a Brushless DC Motor (BLDCM), showcasing three primary control strategies: Adaptive Speed Control, Model Predictive Control (MPC), and Sliding Mode Control (SMC). Each of these controllers aims to maintain the motor's speed at a desired reference level, adjusting based on the error signal calculated by comparing the reference speed with the motor's actual speed. The system begins with a power source supplying input voltage to an inverter, which converts the DC power into AC signals, suitable for BLDC motor operation.

The Adaptive Speed Control, MPC, and SMC methods each receive the error signal and process it independently to generate control actions that minimize speed error. Each controller is connected to a comparator that calculates the difference between the reference and actual speeds, providing feedback for corrective adjustments. The controllers' output signals are then sent to the Gate Pulses block, which manages the inverter's switching actions to regulate the motor's phase voltages, thereby adjusting the motor's speed. The load connected to the BLDC motor further impacts the system, influencing its response under different operational conditions. This structured setup enables a comparative analysis of the control strategies' performance in terms of speed control, stability, and robustness across various load conditions.

4. Results

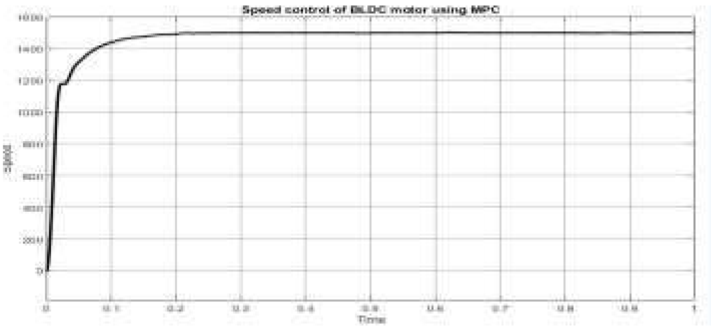

Fig. Graph of by Model Predictive Control (MPC)

The graph illustrates the speed response of a BLDC motor controlled by Model Predictive Control (MPC). Starting from zero, the motor's speed rapidly reaches the target of approximately 1500 units within about 0.2 seconds, showing minimal overshoot and a smooth stabilization. This demonstrates that MPC offers fast, stable control with minimal oscillations, effectively maintaining the desired speed throughout the observed period.

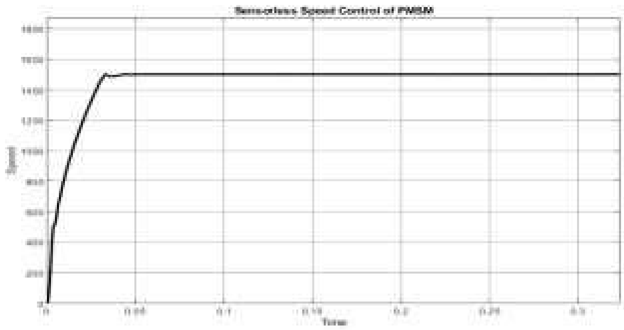

Fig . Graph of sensorless control

The graph displays the speed response of a Permanent Magnet Synchronous Motor (PMSM) under sensorless control. Starting from zero, the motor speed rapidly reaches approximately 1600 units within about 0.05 seconds, demonstrating quick acceleration. The response shows minimal overshoot and smoothly stabilizes at the target speed, indicating that the sensorless control system effectively maintains stable operation without the use of speed sensors, achieving fast and steady control.

5. Conclusion

In summary, this comparative study underscores the unique strengths and limitations of Adaptive PID, Sensorless, and Model Predictive Control (MPC) methods for managing Brushless DC (BLDC) motors in UAV applications. The Adaptive PID controller offers the fastest response with quick settling and rise times, but its notable overshoot and undershoot can lead to fluctuations around the setpoint, which may not suit applications requiring steady control. In contrast, the Sensorless controller provides a more balanced approach, with moderate response times, low overshoot, and steady performance, making it an effective option for applications needing stable control without sensors. The MPC controller, though slower in its response times, achieves superior stability with minimal overshoot and undershoot, maintaining the target speed with very little deviation—ideal for scenarios where precise and stable control is crucial, such as energy-sensitive, long-duration UAV missions. Thus, selecting an appropriate control strategy should align with UAV-specific operational needs, balancing speed, stability, and energy efficiency to meet mission and environmental requirements. .

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