



A Survey on Control Strategies for Brushless DC Motors: Proportional-Integral-Derivative and Field-Oriented Control Techniques in Electronic Systems

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ABSTRACT:

Brushless DC (BLDC) motors are widely used in modern electronic systems due to their high efficiency, compactness, and reduced maintenance requirements. As demand grows in domains such as electric vehicles, drones, home appliances, and industrial automation, the need for robust and precise control strategies becomes increasingly critical. This paper presents a comprehensive survey of two prominent control methodologies for BLDC motors: the Proportional-Integral-Derivative (PID) controller and Field-Oriented Control (FOC). The survey begins with an overview of BLDC motor structure, working principles, and electronic commutation. It then investigates the theoretical foundations, implementation techniques, and tuning processes of both PID and FOC methods. Emphasis is placed on their role in improving dynamic response, torque regulation, speed stability, and overall performance in embedded and real-time systems. Furthermore, this paper analyzes hardware implementation considerations, sensor versus sensorless configurations, and computational trade-offs associated with digital control systems. Comparative studies are reviewed to highlight the advantages and limitations of each control strategy. Lastly, the paper discusses emerging trends including adaptive control, AI-based optimization, and integration with IoT enabled motor drivers. This survey aims to provide researchers, engineers, and system designers with a detailed reference to optimize BLDC motor control within electronic and mechatronic applications.

Keywords: Brushless DC Motor (BLDC), Proportional-Integral-Derivative (PID) Control, Field-Oriented Control (FOC), Embedded Systems, Electronic Motor Control, Real-Time Systems, Sensorless Control, Mechatronics, Power Electronics, Digital Control.

1. Introduction

The increasing reliance on energy-efficient and high-performance electric drives in modern electronic systems has led to the widespread adoption of Brushless DC (BLDC) motors. These motors offer numerous advantages over traditional brushed motors, including higher efficiency, longer lifespan, lower electromagnetic interference, and superior torque-to-weight ratio. As a result, BLDC motors have become a cornerstone in applications ranging from electric vehicles (EVs) and drones to household appliances, medical devices, and industrial automation. Despite their advantages, the performance of BLDC motors heavily depends on the effectiveness of the control algorithms used for speed regulation, torque production, and position accuracy. The absence of brushes necessitates an external electronic controller for commutation, making advanced control strategies not only useful but essential. Two such control techniques, Proportional-Integral Derivative (PID) control and Field-Oriented Control (FOC) are widely studied and implemented due to their ability to enhance motor response, minimize steady-state error, and handle system disturbances. The PID controller is one of the most popular control strategies due to its simplicity, ease of tuning, and effective performance in linear systems. On the other hand, FOC, also known as vector control, represents a more sophisticated approach that enables decoupled control of torque and flux, thereby mimicking the performance of a DC motor and optimizing efficiency under varying loads and speeds. This survey aims to present a holistic view of these control techniques in the context of BLDC motors. The paper begins with an overview of BLDC motor fundamentals, followed by a detailed discussion on the working principles, tuning methods, and real-time implementation aspects of PID and FOC. Further, a comparative analysis is provided to highlight their performance trade-offs, challenges in embedded implementation, and suitability across different application domains. Lastly, the paper explores current research directions and emerging trends, including sensorless control and AI-based motor tuning, that are shaping the future of motor control in electronics.

2. Brushless DC Motor Fundamentals

Brushless DC (BLDC) motors represent a class of synchronous electric motors that operate using direct current (DC) supplied through an electronic controller, as opposed to relying on brushes and a mechanical commutator for current switching. This design innovation eliminates the mechanical wear points common in traditional brushed motors, enhancing performance characteristics such as reliability, efficiency, and control precision. Because of these attributes, BLDC motors are extensively employed in modern electronic systems ranging from electric vehicles to industrial automation and consumer electronics, particularly where compactness, longevity, and precise control are essential.

A. Construction and Working Principle

A BLDC motor typically consists of two main components: a rotor embedded with permanent magnets and a stator made up of multiple windings. These motors are often available in two primary configurations—in-runner, where the rotor is enclosed within the stator, and out-runner, where the stator is situated inside the rotor. Unlike brushed motors that perform mechanical commutation through contact between brushes and a commutator, BLDC motors achieve commutation electronically. This is facilitated through rotor position feedback, obtained via Hall-effect sensors or estimated in sensorless designs using back-EMF signals. The electronic controller energizes the stator windings in a specific sequence, generating a rotating magnetic field. The rotor, attracted to this rotating field, follows its motion, thereby producing rotational output. Control of the commutation sequence is commonly achieved using microcontrollers or digital signal processors (DSPs), which allow high levels of precision and adaptability, making these motors ideal for integration with embedded control systems.

B. Advantages Over Brushed Motors

BLDC motors offer numerous advantages when compared to traditional brushed motors, primarily due to the elimination of brushes. Without mechanical contact elements, friction and wear are significantly reduced, leading to higher efficiency and torque output per watt. The absence of arcing and brush noise also results in quieter operation. Furthermore, the lack of brush maintenance enhances motor reliability and longevity. These motors exhibit superior speed-torque characteristics and are well-suited for applications that demand low maintenance and high operational stability. As such, BLDC motors are widely adopted in aerospace, medical devices, electric vehicles, robotics, and other embedded systems requiring precise motion control and extended service life.

C. Types of BLDC Motor Configurations

BLDC motors can be categorized based on several design and operational aspects. The most prevalent type is the three-phase motor, although single-phase and multi-phase configurations are also used in specialized applications. Another important classification concerns the winding connection—either Wye (star) or Delta. Wye-connected motors typically offer better low-speed torque and efficiency, while Delta-connected motors provide higher speed capabilities. Additionally, BLDC motors may be either sensor-based or sensorless. Sensor-based motors utilize physical devices like Hall sensors to detect rotor position, offering better control at low speeds. In contrast, sensorless designs estimate rotor position using voltage and current feedback, which simplifies construction and enhances reliability in rugged or cost-sensitive applications.

D. Control Challenges

Despite their advantages, BLDC motors present specific challenges in control and operation. One of the primary concerns is the accurate estimation of rotor position, especially in sensorless configurations where low-speed operation is particularly difficult. Another common issue is torque ripple, which can lead to vibration and acoustic noise in precision applications. Maintaining consistent speed under variable load conditions and managing the non-linear dynamics associated with motor parameters like inductance, resistance, and back-EMF further complicate control. To address these challenges, advanced control strategies such as Proportional-Integral-Derivative (PID) control and Field-Oriented Control (FOC) are employed. These algorithms enhance performance by ensuring smooth torque delivery, improved transient response, and robust operation under varying conditions.

3. Proportional-Integral-Derivative (PID) Control

The Proportional-Integral-Derivative (PID) controller is one of the most commonly used control strategies in motor control applications due to its simplicity, intuitive design, and reliable performance. In the context of BLDC motor control, PID controllers are often employed to regulate speed, position, or current. This classical control approach works by continuously calculating the error between a desired setpoint and the actual motor response, and applying corrective control actions to minimize the deviation over time. PID controllers adjust motor behavior based on three key aspects of error: the present error (proportional), the accumulation of past errors (integral), and the rate at which the error is changing (derivative). The proportional component reacts to the magnitude of the error, the integral component eliminates steady-state error by accounting for past values, and the derivative component predicts future trends by observing the rate of change. This combination allows the PID controller to provide a balance of responsiveness, stability, and accuracy. In embedded systems and digital electronics, PID controllers are typically implemented in firmware using microcontrollers or digital signal processors. Tuning of the PID parameters is essential to ensure optimal motor performance and stability. Several methods exist for tuning, ranging from manual adjustment and heuristic methods like Ziegler-Nichols to automated software-based techniques. While PID control performs adequately in many applications, it has limitations when applied to highly dynamic or nonlinear systems, which are common in BLDC motor environments. For instance, sudden changes in load or speed can cause overshoot or oscillations if the controller is not properly tuned. Nonetheless, the widespread use of PID control in industrial and consumer electronics demonstrates its practicality. It is particularly advantageous in cost-sensitive and computationally constrained systems, such as small-scale robotics, home appliances, and electric tools, where complex control algorithms may not be feasible.

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4. Field-Oriented Control (FOC)

Field-Oriented Control (FOC), also referred to as vector control, represents a more advanced control strategy that enables high-performance operation of AC motors, including BLDC and PMSM types. FOC achieves superior motor control by decoupling torque and flux components, allowing them to be controlled independently. This results in smoother and more precise control of the motor, especially under varying load and speed conditions. The FOC technique involves transforming the three-phase currents from the stator into a two-axis reference frame that rotates with the rotor. By aligning this reference frame with the rotor's magnetic field, the controller can effectively regulate torque-producing and magnetizing currents separately. Once the desired torque and flux levels are set, these control values are converted back to three-phase signals and used to drive the motor via a voltage source inverter. One of the main advantages of FOC is its ability to deliver consistent torque with minimal ripple, even at low speeds. This makes it suitable for applications requiring high precision and responsiveness, such as electric vehicles, aerospace systems, advanced robotics, and industrial automation. FOC also enhances the dynamic performance of the motor, improving both acceleration and deceleration capabilities. The implementation of FOC typically requires more powerful processing capabilities than traditional PID control. Microcontrollers with integrated mathematical libraries, digital signal processors, or FPGAs are often used to perform the real-time transformations and control loop calculations. Moreover, FOC systems often require accurate rotor position feedback, which is typically achieved using encoders or resolvers. In cost-sensitive applications, sensorless techniques based on back electromotive force (EMF) or model observers are also employed. Despite its computational complexity, the benefits of FOC—such as high efficiency, superior torque control, and robust performance under dynamic conditions—have led to its widespread adoption in modern embedded electronic systems. Its application in BLDC motors continues to grow, particularly as processing capabilities and development tools become more accessible to designers and researchers.

5. Comparative Analysis of PID and Field-Oriented Control for BLDC Motor Drives

When comparing Proportional-Integral-Derivative (PID) control and Field-Oriented Control (FOC) in the context of BLDC motor drives, it becomes clear that both strategies have distinct characteristics, strengths, and limitations depending on the application requirements and system constraints. PID control, due to its straightforward implementation and low computational demand, remains the preferred choice in systems where simplicity, cost-effectiveness, and ease of tuning are the primary concerns. Applications such as household appliances, low-end automation, and consumer-grade robotics benefit from PID's rapid deployment and adequate performance in less complex operating conditions. However, the method shows its limitations in environments with variable loads, fast transient responses, and non-linear behavior. PID controllers often struggle with torque ripple and may become unstable under high-speed or low-speed edge cases if not tuned properly. On the other hand, Field-Oriented Control offers a more sophisticated and precise method of managing BLDC motor operation. It allows for independent control of the motor's torque and magnetic flux, leading to significantly improved efficiency, reduced torque ripple, and smooth dynamic performance across all speed ranges. FOC is highly effective in high-end applications that demand exacting standards for motor behavior, such as electric vehicles, medical equipment, aerospace systems, and high-performance industrial machinery. Its ability to operate with precision under varying loads and conditions makes it especially valuable in mission-critical and real-time control systems. Nevertheless, the implementation of FOC requires advanced hardware and development tools. It demands higher processing power, complex mathematical transformations, and often real-time position feedback, which may not be feasible for low-budget or resource-constrained systems. Sensorless FOC techniques can mitigate some cost concerns but typically add complexity to the software layer and require robust signal processing capabilities. Overall, the choice between PID and FOC is not merely technical but also contextual. Designers must evaluate trade-offs between performance, complexity, hardware availability, and cost. While PID remains relevant and reliable in many general-purpose motor control applications, FOC represents the future for precision electronics and embedded control systems, particularly as embedded processors and control algorithms continue to evolve.

6. Applications

Brushless DC (BLDC) motors, along with advanced control techniques like PID and Field-Oriented Control (FOC), are widely deployed across diverse domains in electronics and embedded systems. Their compact size, high torque-to-weight ratio, efficiency, and reliability make them well-suited for numerous precision-driven applications.

In the automotive industry, BLDC motors controlled via FOC have become a core component of electric vehicles (EVs) and hybrid electric vehicles (HEVs), powering everything from traction systems to auxiliary functions like electric steering, pumps, and fans. The ability of FOC to deliver precise torque control and smooth acceleration enhances vehicle performance and driver comfort. Meanwhile, PID controllers are still used for subsystems requiring simpler control, such as climate control and seat adjustment mechanisms.

Industrial automation is another significant domain where BLDC motors, particularly under FOC control, enable high-performance motion systems in CNC machines, conveyor belts, robotic arms, and pick-and-place systems. These applications benefit from FOC's real-time control and energy efficiency. PID control remains prevalent in legacy systems and simpler automation tasks where the dynamics are relatively stable and predictable.

In consumer electronics, applications such as drones, washing machines, and cooling fans integrate BLDC motors for their quiet operation and low maintenance. PID controllers are often sufficient in such contexts due to cost constraints and relatively less dynamic requirements. However, the growing demand for precision and user-defined behaviours has led to increasing interest in FOC even in these lower-end applications.

Medical devices represent another critical field where BLDC motors controlled via FOC are essential for devices such as ventilators, surgical robots, and imaging systems. These applications demand high accuracy, smooth operation, and safety—qualities that FOC can offer. On the other hand, simpler medical equipment may rely on PID controllers due to their proven reliability and ease of deployment.

In the aerospace sector, the use of BLDC motors in actuators, gimbals, and control surfaces is rising, where compactness and dependability are essential. FOC offers the performance required for mission-critical tasks, while PID finds use in subsystems with more predictable load conditions. Lastly, research and development platforms—particularly in academia and prototyping environments—frequently use both PID and FOC-based BLDC motor control setups. These platforms help engineers and researchers evaluate system responses, study control theory, and test new motor applications in embedded electronics, contributing to advancements in the field. In conclusion, the application landscape for BLDC motors with PID and FOC control is vast and rapidly expanding. The choice of control strategy is often dictated by specific application requirements, system complexity, and resource availability, making it essential for engineers to understand both paradigms for optimal system design.

7. Challenges and Future Trends

Despite the widespread use and proven capabilities of Brushless DC (BLDC) motors, their control techniques—particularly Proportional-Integral-Derivative (PID) and Field-Oriented Control (FOC)—face several challenges that need to be addressed for continued performance improvement and adoption in more advanced applications.

A. Challenges

One of the primary challenges with PID control is its inherent limitation in handling highly dynamic or nonlinear systems, which are commonly encountered in BLDC motor drives under varying load conditions. The accuracy of the controller is highly dependent on precise tuning of its parameters (proportional, integral, and derivative gains), which can be difficult to achieve in real-time or under changing environmental conditions. Additionally, PID controllers often struggle to reduce torque ripple and may cause performance degradation at low speeds or when dealing with sudden changes in load or input parameters. On the other hand, while FOC provides superior performance, it comes with its own set of challenges. The implementation of FOC requires high processing power for real-time mathematical transformations and torque control, often necessitating specialized hardware such as digital signal processors (DSPs), microcontrollers with floating-point units (FPUs), or field-programmable gate arrays (FPGAs). This hardware complexity, combined with the need for accurate rotor position feedback, increases both the cost and system complexity. For sensorless FOC, the challenge lies in ensuring reliable rotor position estimation without relying on costly sensors like encoders or resolvers, which can compromise accuracy and performance, especially at low speeds or during startup. In both control techniques, the integration of power electronics (inverters) poses another challenge. High-frequency switching and electromagnetic interference (EMI) from inverters can affect the stability of the motor control, leading to issues like voltage spikes, reduced efficiency, and increased wear on motor components. Additionally, designing efficient power stages that minimize heat dissipation and maximize performance remains a critical challenge, especially in high-power applications such as electric vehicles.

B. Future Trends

The future of BLDC motor control is set to be shaped by several emerging trends, primarily driven by advances in digital electronics, machine learning, and system integration. One of the key trends is the integration of sensorless control techniques for both PID and FOC. Sensorless operation not only reduces the cost of systems by eliminating the need for physical sensors but also simplifies the design and enhances reliability. Recent advancements in back electromotive force (EMF) sensing and sliding mode observers are paving the way for more robust sensorless algorithms. The increasing processing power of microcontrollers and digital signal processors will also enable more sophisticated adaptive control systems. These systems can dynamically adjust control parameters in real-time to account for changing load conditions, system aging, and external disturbances. This would overcome one of the major limitations of traditional PID control, improving the robustness and flexibility of motor systems. Another exciting development is the incorporation of machine learning algorithms into motor control. Techniques such as neural networks and deep learning could be employed to optimize control strategies, predict system behavior, and adaptively tune control parameters based on real time data, effectively learning the optimal control approach over time. This could significantly enhance performance and efficiency, particularly in applications that involve unpredictable or variable loads.

Further advancements in power electronics will also play a pivotal role in the evolution of BLDC motor control. More efficient inverters with improved switching devices, such as wide-bandgap semiconductors (e.g., silicon carbide (SiC) and gallium nitride (GaN)), will enable more compact, reliable, and energy-efficient systems capable of operating at higher switching frequencies with reduced EMI. These advancements will make BLDC motors even more attractive for high-power applications, such as renewable energy systems and electric aircraft. Finally, the continuous push for sustainability and energy efficiency in electronics will further propel the development of high-efficiency BLDC motor drives. The optimization of control algorithms and power stages to reduce energy consumption, coupled with innovative cooling and heat management techniques, will extend the operational life of BLDC motors and contribute to greener technologies across industries.

Conclusion

In this survey paper, we explored the role of Brushless DC (BLDC) motors in modern electronics, focusing on two prominent control techniques—Proportional-Integral-Derivative (PID) control and Field-Oriented Control (FOC). BLDC motors, with their high efficiency, reliability, and compact size, have become integral components in various industries, including automotive, industrial automation, consumer electronics, medical devices, and aerospace. Both PID and FOC offer unique advantages, and the choice between them is largely influenced by the specific performance requirements of the application, the available resources, and the complexity of the system. PID control remains a preferred option for simpler, less dynamic

applications, where cost effectiveness and ease of implementation are key considerations. It offers satisfactory performance in systems with predictable load conditions but struggles to maintain efficiency and stability under more complex or variable operating environments. In contrast, FOC provides superior precision, smoother operation, and enhanced efficiency, making it ideal for high-performance applications that demand real-time control and low torque ripple. However, its implementation requires more advanced hardware and processing power, making it less suitable for cost-sensitive or resource constrained systems. The paper also highlighted the challenges associated with both control strategies, including the need for precise tuning in PID control and the hardware complexity of FOC systems. As BLDC motor technology evolves, innovations such as sensorless control, adaptive control algorithms, and machine learning are expected to address these challenges, enhancing both performance and cost effectiveness. Furthermore, advancements in power electronics, particularly with the use of wide bandgap semiconductors, are set to improve the efficiency and reliability of BLDC motor drives, enabling their use in even more demanding applications. Looking to the future, the demand for energy-efficient, high-performance systems will drive continued research and development in motor control technologies. As the capabilities of microcontrollers and digital signal processors continue to expand, the integration of advanced control techniques and optimization algorithms will play a crucial role in shaping the next generation of BLDC motor applications. In conclusion, the control of BLDC motors is an ever-evolving field that promises significant contributions to the future of electronics and embedded systems. The choice of control strategy will continue to depend on the specific needs of each application, with PID and FOC representing two key approaches that offer distinct trade-offs in terms of complexity, performance, and system requirements.

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