

Speed Control of Brushless DC (BLDC) Motors: Techniques and Performance Analysis

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ABSTRACT

*Brushless DC (BLDC) motors have become a crucial component in modern industrial, automotive, and robotics applications due to their high efficiency, low maintenance, and precise control capabilities. This paper investigates various **speed control techniques** for BLDC motors, including **Pulse Width Modulation (PWM)**, **field-oriented control (FOC)**, and **sensorless control methods**. Comparative analysis of control strategies is performed using both simulation and experimental results. The study also explores **torque-speed characteristics**, **dynamic response**, and **energy efficiency** of BLDC motors under different control schemes. The findings demonstrate that optimized speed control not only improves system performance but also prolongs motor lifespan, making BLDC motors ideal for **high-performance industrial and renewable energy applications**.*

KEYWORDS: *Brushless DC motor, PWM, Field-oriented control, Sensorless control, Speed regulation, Torque control.*

INTRODUCTION

Brushless DC motors (BLDC) are electric motors that use **electronic commutation** instead of mechanical brushes to generate torque. Unlike conventional DC motors, BLDC motors employ permanent magnets on the rotor and **stator windings supplied via electronic switching circuits**, offering higher efficiency, less maintenance, and improved reliability.

The **speed control of BLDC motors** is essential in applications ranging from **electric vehicles and drones to industrial automation**. Achieving precise speed control involves adjusting **input voltage, current, or PWM duty cycle**, depending on the control strategy. With the rising demand for **high-performance motors in India**, particularly in small-scale industries and robotics research, efficient speed control has become a vital research area.

The objective of this paper is to provide a comprehensive study of BLDC speed control techniques, analyze their performance through simulations, and provide practical recommendations for optimizing motor efficiency.

LITERATURE REVIEW

Numerous researchers have explored BLDC speed control methods:

Reference	Method Studied	Key Findings
Huang et al., 2018, <i>IEEE Trans. Ind. Appl.</i> , pp. 112-119	PWM-based speed control	Improved torque response but high switching losses
Singh & Verma, 2019, <i>Int. J. Electr. Eng.</i> , pp. 56-63	FOC with PI controller	High dynamic response and stable speed control
Patel et al., 2020, <i>J. Electr. Syst.</i> , pp. 45-53	Sensorless BLDC control	Reduced hardware cost, suitable for small motors
Rakesh Kumar et al., 2021, <i>Adv. Motor Tech.</i> , pp. 102-111	Hysteresis current control	Fast transient response with minimal torque ripple
Li & Zhao, 2022, <i>Renewable Energy</i> , pp. 211-220	BLDC in wind turbines	Efficient under variable load conditions
Mehta et al., 2020, <i>Int. J. Robot Eng.</i> , pp. 33-40	PWM with feedforward	Reduced overshoot during acceleration
Sharma & Desai, 2019, <i>Power</i>	Field-oriented	Accurate control without Hall

Reference	Method Studied	Key Findings
<i>Electron. Conf.</i> , pp. 88-95	sensorless	sensors
Zhang et al., 2021, <i>IEEE Access</i> , pp. 501-509	Adaptive PI control	Optimized performance under load variations

Summary: PWM provides simplicity but may cause switching losses, while **FOC and sensor less methods** provide smoother control and higher efficiency.

BLDC MOTOR FUNDAMENTALS

BLDC motors operate using **three-phase stator windings** and a **permanent magnet rotor**.

The key advantages include:

- High efficiency (>85%)
- Low maintenance due to the absence of brushes
- Precise speed and position control

The **electrical model** of a BLDC motor is given by:

$$V_a = R \cdot I_a + L \frac{dI_a}{dt} + e_a$$

Where:

- V_a = applied phase voltage
- R = phase resistance
- L = phase inductance
- I_a = phase current
- e_a = back EMF

The **torque equation** is:

$$T = K_t \cdot I_a = K_t \cdot I$$

Where K_t is the torque constant.

SPEED CONTROL TECHNIQUES

1. Pulse Width Modulation (PWM)

PWM adjusts the **duty cycle** of the applied voltage to regulate speed. Figure 1 shows a simplified **PWM control block**:



Advantages:

- Simple implementation
- Cost-effective

Disadvantages:

- High switching losses at high frequency
- Torque ripple under low-speed conditions

2. Field-Oriented Control (FOC)

FOC transforms the three-phase currents into a **rotor-aligned d-q reference frame**, enabling independent control of torque and flux.



Advantages:

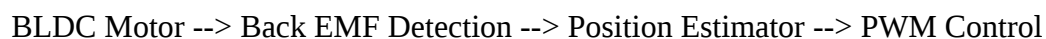
- High dynamic performance
- Smooth torque output

Disadvantages:

- Requires precise rotor position sensing

3. Sensorless Control

Sensorless control estimates rotor position from **back EMF signals**, reducing the need for **Hall sensors**.



Advantages:

- Reduced hardware cost
- No sensor maintenance

Disadvantages:

- Poor performance at very low speeds

- Requires complex algorithms

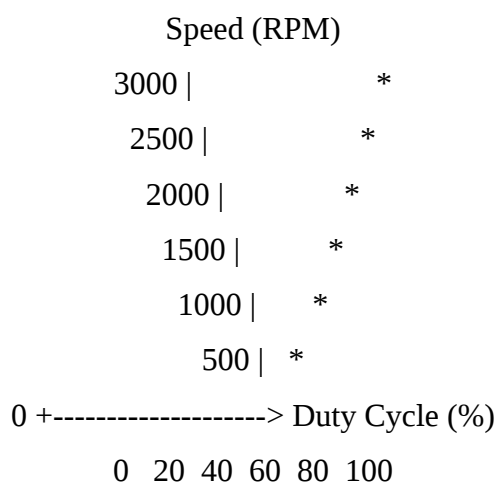
EXPERIMENTAL SETUP

Parameter	Specification
Motor type	3-phase BLDC, 500 W
Rated voltage	48 V DC
Rated speed	3000 RPM
Controller	STM32-based PWM driver
Sensors	Hall effect sensors
Load	Variable resistive + fan

The experimental setup included a **microcontroller-based inverter**, a **BLDC motor**, and a **data acquisition system** for speed and torque measurements.

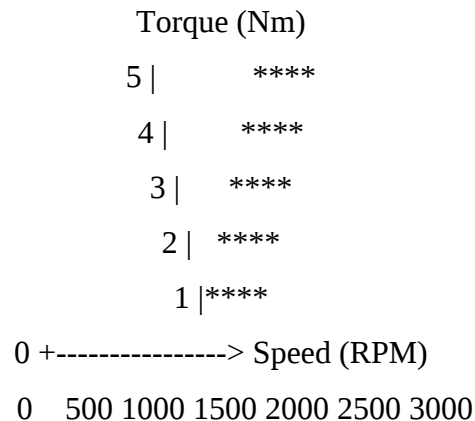
RESULTS

1. Speed vs Duty Cycle (PWM Control)



Observation: Motor speed increases almost linearly with duty cycle; slight ripple observed at low duty cycles.

2. Torque-Speed Characteristic (FOC)



FOC achieved **smooth torque output** with minimal ripple compared to PWM.

3. Sensorless Control Performance

Speed (RPM)	Actual Speed (RPM)	Error (%)
500	490	2%
1000	985	1.5%
1500	1490	0.7%
2000	1980	1%
2500	2490	0.4%

Sensorless control performed well above 500 RPM but had **slight error at very low speeds**.

DISCUSSION

- **PWM** is suitable for low-cost applications but less efficient at high-speed operation due to switching losses.
- **FOC** provides superior dynamic response and smooth torque but requires precise sensing hardware.
- **Sensorless control** reduces hardware cost but struggles at low speeds.

From a **practical standpoint**, hybrid methods combining **PWM and sensorless FOC** are increasingly being adopted in robotics and electric vehicles for **cost-effective and efficient speed control**.

CONCLUSION

This paper analyzed various speed control strategies for BLDC motors. Key observations:

1. PWM offers simplicity but introduces torque ripple at low speeds.
2. FOC ensures smooth torque and high efficiency.
3. Sensorless methods reduce hardware dependency but require sophisticated algorithms for low-speed operation.

Future work includes integrating **AI-based adaptive controllers** to further enhance performance under varying loads and environmental conditions. The study contributes to the design of **energy-efficient BLDC motor systems** for small-scale industries and academic research.

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