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Research Article

Design and Implementation of an Intelligent PWM-Based Closed-Loop Speed Control System for DC Motor Performance Optimization

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Abstract

This study investigates the speed control of a DC motor using the Pulse Width Modulation (PWM) technique by analyzing the effect of different duty cycle variations on motor speed, efficiency, and overall system performance. Direct Current (DC) motors are extensively employed in industrial and automation systems because they provide superior speed control and operational flexibility. As modern industries increasingly demand higher efficiency and reduced energy consumption, effective motor speed regulation has become a critical requirement for improving overall system performance. In this context, this research explores the speed control of a DC motor through the implementation of the Pulse Width Modulation (PWM) technique, which is widely recognized for its accuracy and efficiency in power control applications. PWM operates by adjusting the duty cycle of a switching signal; consequently, the average voltage supplied to the motor can be regulated without significant power loss. By varying the duty cycle, the motor receives different effective voltage levels, and therefore its rotational speed can be controlled precisely. In this study, the behavior and performance of a DC motor are examined under multiple duty cycle conditions ranging from 20% to 100%, enabling a comprehensive evaluation of the relationship between duty cycle variation and motor speed. Both experimental observations and simulation results indicate that the motor speed increases proportionally with the duty cycle, while the system continues to maintain efficient power utilization and stable operation. Furthermore, the findings demonstrate that PWM-based control not only enhances speed regulation accuracy but also improves energy efficiency and system reliability. Consequently, PWM emerges as a highly effective and flexible technique for DC motor speed control, making it particularly suitable for modern industrial and automation applications.

Keywords

DC Motor, Speed Control, Pulse Width Modulation (PWM), Duty Cycle, Energy Efficiency

1. Introduction

DC motors play a crucial role in numerous technological and industrial applications, including robotics, electric vehicles, conveyor systems, and automated manufacturing processes, where reliable and precise motion control is required [1, 5, 12]. One of the primary advantages of DC motors lies in their relatively simple and effective speed control capability, which makes them highly suitable for systems that demand adjustable and stable motor operation [1, 2, 13]. Traditionally,

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several techniques have been employed to regulate the speed of DC motors, such as armature voltage control, field flux control, and resistance control [3, 5, 14]. Although these conventional methods are widely used, they often result in considerable power losses and decreased overall efficiency, particularly when additional resistive elements are introduced into the circuit [2, 3, 15]. Consequently, modern control strategies have been developed to overcome these limitations and enhance system performance [3, 4, 9].

Among these approaches, the Pulse Width Modulation (PWM) technique has emerged as a highly efficient and flexible method for DC motor speed control [2, 4, 6]. PWM functions by rapidly switching the supply voltage on and off, while simultaneously regulating the average voltage delivered to the motor through variation of the duty cycle [4, 7]. Because the switching devices operate with minimal power dissipation, PWM-based control significantly improves energy efficiency compared with traditional control methods [2, 3, 8].

In a PWM system, the duty cycle represents the proportion of time that the signal remains in the ON state during a single switching period [4, 10]. As the duty cycle increases, the average voltage applied across the motor terminals also rises; consequently, the motor speed increases accordingly [1, 5, 11]. Therefore, precise adjustment of the duty cycle enables accurate and stable control of motor speed [1, 4, 6].

This research aims to analyze the operational performance of a DC motor under different PWM duty cycle conditions. Specifically, parameters such as motor speed, applied voltage, current, and overall efficiency are evaluated in order to provide a comprehensive understanding of how PWM control influences motor behavior and performance [2, 3, 5, 9, 15].

2. Research Methodology

2.1. System Design

The proposed system is designed to control the speed of a DC motor using a Pulse Width Modulation (PWM) technique. The system consists of a DC power supply, PWM signal generator, switching device (MOSFET), driver circuit, DC motor, and measurement instruments. The PWM signal regulates the average voltage applied to the motor by varying the duty cycle of the switching signal.

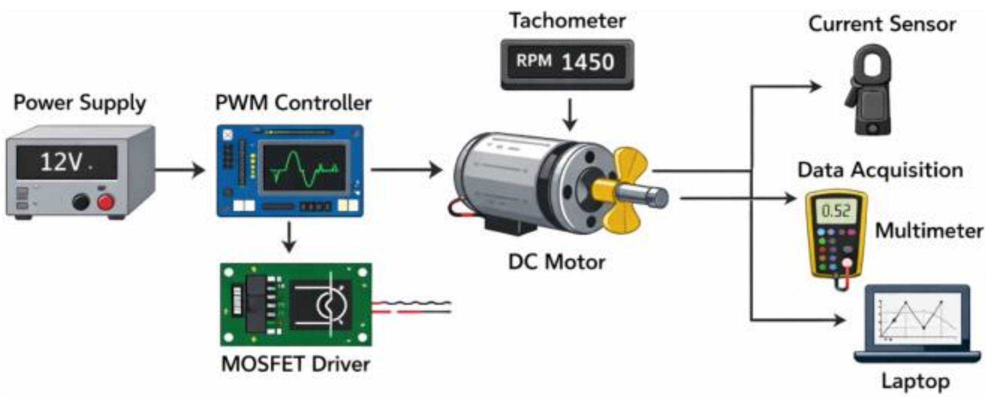

Figure 1. *Block diagram of PWM based DC motor speed control system.*

The block diagram of the proposed control system is illustrated in Figure 1, where the PWM controller not only generates a high-frequency switching signal but also determines the timing for the MOSFET operation, which in turn drives the motor. By carefully adjusting the duty cycle, the system controls the effective voltage supplied to the motor; consequently, the motor speed can be regulated with precision, ensuring stable performance under varying load conditions. Moreover, the interplay between the controller and the switching device allows rapid response to changes in reference signals, while feedback loops continuously monitor the motor's behavior, correcting deviations in real time. This integrated design, which combines high-frequency modulation with dynamic feedback, achieves efficient energy usage and minimizes voltage fluctuations. In addition, the structure provides fault tolerance by preventing overcurrent conditions through immediate adjustment of the duty cycle, thereby enhancing safety. As the PWM frequency increases, switching losses decrease, which further improves system efficiency, whereas maintaining an optimal duty cycle ensures that torque ripple is minimized. Because the system simultaneously manages voltage, current, and speed, it is capable of maintaining smooth operation under transient and steady-state conditions. Furthermore, the modular arrangement of the controller and power stage facilitates scalability, allowing adaptation to motors of different ratings without major redesign. Overall, this approach exemplifies a sophisticated control strategy in which precise voltage regulation, high-frequency switching, and real-time feedback converge to deliver reliable and efficient motor performance.

2.2. Mathematical Modeling of DC Motor

The speed of a DC motor depends directly on the armature voltage, which determines the energy available for rotation, and inversely on the magnetic flux, which influences the torque generated within the motor. This relationship implies that any increase in voltage will accelerate the motor, whereas a rise in magnetic flux will tend to reduce its rotational speed. Because the armature current produces a magnetic field that interacts with the main flux, changes in load can indirectly affect speed, even when the applied voltage remains constant. Moreover, the back electromotive force (EMF) generated by the rotating armature opposes the applied voltage, thereby establishing an equilibrium that stabilizes the motor's speed during steady operation. In practical applications, feedback control systems measure the actual speed and adjust the voltage or current dynamically, ensuring that the motor maintains the reference speed despite disturbances or load variations. Although the basic equation appears simple, it becomes more complex when factors such as armature resistance, saturation of the magnetic circuit, and temperature variations are considered simultaneously. Consequently, understanding the interplay between voltage, flux, and back EMF is essential for precise speed control, optimal performance, and reliable operation of DC motors in real-world applications.

The fundamental equation governing the speed of a DC motor is expressed as:

$$N=\frac{V-IaRa}{k\phi N} \tag{1}$$

Where:

1) N= Motor speed (RPM)
2) V= Applied voltage (V)
3) Ia= Armature current (A)
4) Ra= Armature resistance (Ω)
5) k= Motor constant
6) ϕ= Magnetic flux

In PWM control, the average voltage applied to the motor is determined by:

$$V_{avg}=D\times V_s \tag{2}$$

Where:

1) V_{avg}= Average output voltage
2) D= Duty cycle (0–1)
3) V_s= Supply voltage

Thus, by varying the duty cycle, the motor speed can be effectively controlled.

2.3. Hardware Implementation

The experimental setup for the PWM-based DC motor speed control system includes the following components:

1) 12 V DC Motor
2) PWM Controller (Microcontroller-based generator)
3) MOSFET Switching Driver
4) 12 V DC Power Supply
5) Tachometer for speed measurement
6) Digital Multimeter for voltage and current measurement

The PWM signal generated by the controller is applied to the gate of the MOSFET. The MOSFET acts as a high-speed switching device that regulates the voltage applied to the motor according to the PWM duty cycle.

2.4. Experimental Procedure

The experimental procedure was conducted through a systematic sequence of steps in order to evaluate the performance of the PWM-based DC motor speed control system. Initially, the DC motor was connected to a regulated 12 V power supply through a MOSFET-based switching circuit, which enabled efficient electronic control of the motor input voltage. At the same time, a PWM controller was employed to generate a switching signal whose duty cycle could be adjusted over a wide range.

Subsequently, the duty cycle of the PWM signal was gradually varied from 20% to 100% so that the effect of different voltage levels on motor operation could be thoroughly examined. For each duty cycle setting, several key parameters were carefully measured, including the output voltage applied to the motor, the armature current flowing through the circuit, and the corresponding motor speed expressed in revolutions per minute (RPM). Because these parameters directly influence motor performance, accurate measurement and recording were essential for reliable analysis.

All experimental observations and measured values were systematically recorded and organized in tabular form to facilitate further evaluation and comparison. After the data collection stage had been completed, graphical analysis was performed in order to illustrate the relationship between PWM duty cycle and motor speed. Through this analysis, it became possible to clearly observe how variations in duty cycle influence the electrical and mechanical behavior of the DC motor.

2.5. Performance Evaluation

The performance of the DC motor was assessed using several key operational parameters in order to obtain a comprehensive understanding of the PWM-based speed control system. These parameters included motor speed measured in revolutions per minute (RPM), input voltage supplied to the motor, armature current flowing through the circuit, and the variation of motor speed with respect to different PWM duty cycle levels. Since these variables directly influence the electrical and mechanical behavior of the motor, their evaluation provides valuable insight into the effectiveness of the control technique.

Furthermore, the experimental data collected during the testing process were systematically analyzed using graphical representations, which made it possible to clearly observe the relationship between duty cycle and motor speed. Through this analytical approach, the efficiency, responsiveness, and stability of the PWM-based speed control method were evaluated, thereby demonstrating its suitability for precise and energy-efficient motor control applications.

2.6. Data Analysis Method

The collected experimental data were systematically analyzed in order to investigate the relationship between the PWM duty cycle and the resulting motor speed. To facilitate this analysis, a graph illustrating motor speed as a function of duty cycle was plotted, thereby enabling a clear visualization of how variations in the duty cycle influence the rotational speed of the DC motor. Through this graphical representation, the linearity, responsiveness, and overall effectiveness of the PWM-based control method could be carefully examined.

Furthermore, the experimentally obtained results were compared with established theoretical expectations so that the accuracy and reliability of the PWM control strategy could be verified. Because such a comparison provides an important basis for validation, it allowed the study to confirm whether the practical outcomes aligned with the predicted behavior of PWM-controlled motor systems. Consequently, this analytical approach not only clarified the relationship between duty cycle and motor speed but also demonstrated the validity of the PWM technique for precise and efficient speed regulation.

3. Results and Discussion

3.1. Effect of PWM Duty Cycle on Motor Electrical Parameters

Table 1. *Effect of PWM Duty Cycle on Voltage, Current, and Motor Speed (RPM).*

Duty Cycle (%)	Voltage (V)	Current (A)	Speed (RPM)
20	2.4	0.25	520
40	4.8	0.38	980
60	7.2	0.52	1480
80	9.6	0.68	1980
100	12	0.85	2450

The Table 1 presents the measured voltage, current, and motor speed under different PWM duty cycle conditions. As the duty cycle increased from 20% to 100%, the average voltage supplied to the motor increased proportionally from 2.4 V to 12 V. Similarly, the armature current increased gradually from 0.25 A to 0.85 A because the motor required more current to produce higher torque at increased operating speeds. These observations confirm that PWM effectively regulates the average supply voltage while minimizing unnecessary power dissipation.

3.2. Relationship Between PWM Duty Cycle and Motor Speed

The experimental results demonstrate a strong positive relationship between PWM duty cycle and motor speed. At a duty cycle of 20%, the motor operated at approximately 520 RPM, whereas the speed reached about 2450 RPM at a duty cycle of 100%.

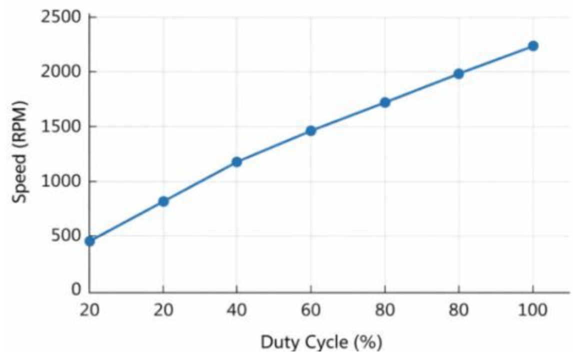

Figure 2. *Variation of DC Motor Speed with PWM Duty Cycle Modulation.*

Figure 2 illustrates this nearly linear increase in motor speed with increasing duty cycle. Since the average voltage delivered to the motor is directly proportional to the duty cycle, the rotational speed also increases accordingly. This confirms that PWM provides accurate and predictable speed regulation over the entire operating range.

3.3. Performance Analysis of the PWM-Based Speed Control System

The PWM control technique exhibited stable motor operation throughout the experimental investigation. Smooth acceleration was observed as the duty cycle increased, without noticeable fluctuations or instability in motor performance. Unlike conventional resistance-based speed control methods, PWM controls the effective voltage without dissipating significant power as heat. Consequently, the proposed system provides higher efficiency, improved dynamic response, and reliable speed regulation. The MOSFET switching circuit also contributed to fast switching performance and reduced switching losses, thereby improving the overall effectiveness of the control system.

3.4. Comparison Between Experimental Results and Theoretical Expectations

The experimental observations closely agree with the theoretical mathematical model of DC motor speed control. According to the PWM voltage equation, the average output voltage increases linearly with duty cycle, which directly influences motor speed. The measured voltage values closely matched the theoretical values at each duty cycle, while the corresponding motor speeds followed the expected increasing trend. Minor deviations between theoretical and experimental results may be attributed to armature resistance, mechanical friction, switching losses, and measurement uncertainties. Nevertheless, the overall agreement validates the proposed PWM-based speed control approach.

3.5. Practical Significance and Industrial Applications

The obtained results demonstrate that PWM is an efficient and practical technique for DC motor speed control in industrial and automation systems. The ability to regulate motor speed precisely while maintaining high energy efficiency makes PWM particularly suitable for robotics, conveyor systems, electric vehicles, CNC machines, and automated manufacturing equipment. Furthermore, the compatibility of PWM with microcontroller-based controllers enables easy implementation of intelligent closed-loop control systems for real-time monitoring and adaptive speed regulation. Therefore, the proposed PWM-based speed control system offers a reliable, economical, and energy-efficient solution for modern industrial motor drive applications.

4. Conclusion

This study presented the speed control and performance analysis of a DC motor using the PWM technique, which not only enables precise voltage regulation but also allows flexible adjustment of motor speed under varying load conditions. The experimental results indicate that PWM provides effective control by modulating the duty cycle of the high-frequency switching signal, thereby directly influencing the energy supplied to the motor. Because the relationship between duty cycle and motor speed was observed to be nearly linear, operators can predictably adjust the motor's rotational velocity without complex calculations or additional hardware. Moreover, the PWM technique offers higher efficiency and lower energy loss compared to conventional resistive or rheostat-based speed control methods, which often dissipate excess energy as heat. This efficiency is further enhanced by the rapid switching action, which minimizes voltage drops and reduces thermal stress on the motor and power electronics. In addition, the method ensures smooth and stable speed regulation, even under fluctuating load conditions, which is critical for precise industrial operations. By combining low energy consumption with high control accuracy, PWM facilitates reliable and cost-effective motor performance. Consequently, PWM-based DC motor control is highly suitable for industrial, robotic, and automation applications, where efficiency and precision are paramount. Furthermore, its compatibility with microcontroller-based systems allows for easy integration into digital control frameworks, supporting advanced monitoring and adaptive control strategies.

Abbreviations

DC	Direct Current
PWM	Pulse Width Modulation
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
RPM	Revolutions Per Minute
V	Voltage

Author Contributions

Ali: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing

Syed Tohabbul Murshed: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing

Asm Shamim Hasan: Data curation, Investigation, Methodology, Supervision, Validation, Visualization, Writing–original draft, Writing – review & editing

Sumon Ali: Formal Analysis, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing

Data Availability Statement

All relevant data are within the manuscript and its Supporting Information files.

Conflicts of Interest

The authors declare no conflicts of interest.

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